Probing Quark-Gluon Plasma with Jets and Flow

Guang-You Qin（秦广友）

Central China Normal University
华中师范大学
Institute of Particle Physics
粒子物理研究所

TDLI/INPAC Joint Theory Seminar
Shanghai Jiaotong Unviersity
上海交通大学
2022年2月24日

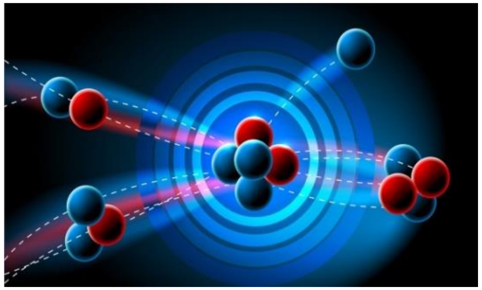
Outline

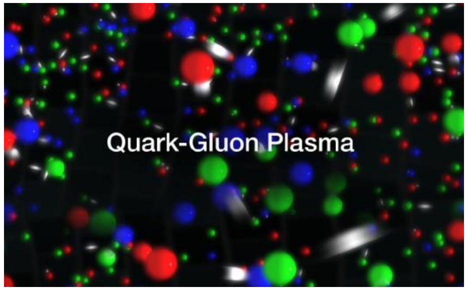
- **Introduction**
  - **Quark-gluon plasma, relativistic heavy-ion collisions**
- **Flow and collective properties**
  - **Yields, spectra, flow, fluctuations, correlations, decorrelations**
- **Jets and jet-medium interaction**
  - **High p_T hadrons, heavy quarks/hadrons, full jets, medium response**
- **Small systems**
  - **Flow and jet quenching**
- **Summary**

Heating up the matter

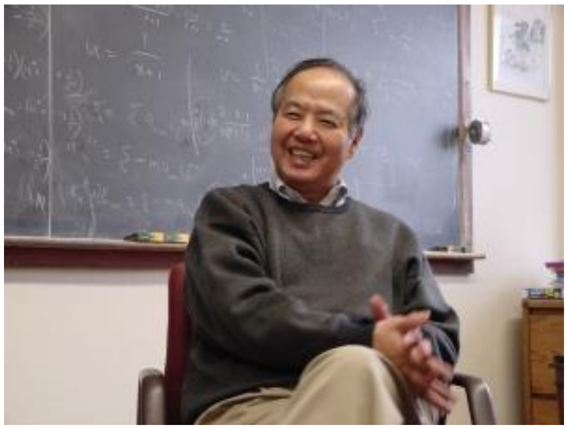
- How does the matter change when heated?
- Increasing temperature increases the kinetic energies of DOFs.
- High enough temperature can break the larger structures (DOFs) by activating more fundamental DOFs.
- Breaking molecules and chemical bonds: 10^3K, burning, flame, torch
- Breaking atoms (to get QED plasma): 10^5K, ironization
- Breaking nuclei: 10^8-10^9K, nuclear reactions
- Breaking nucleons (to get QGP): 10^{12}K, relativistic nuclear collisions

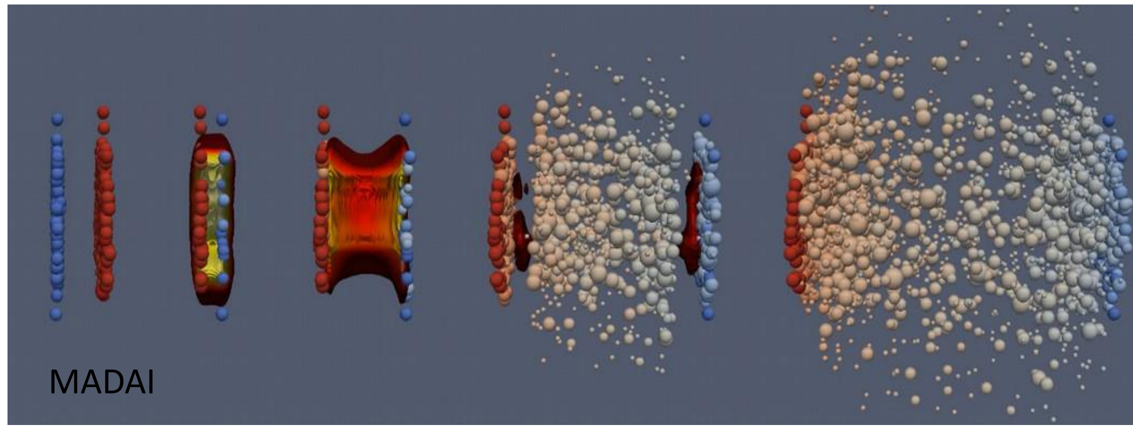
$$k_B = 8.62 \times 10^{-5} \frac{eV}{K}, 1eV = 1.16 \times 10^4 K$$

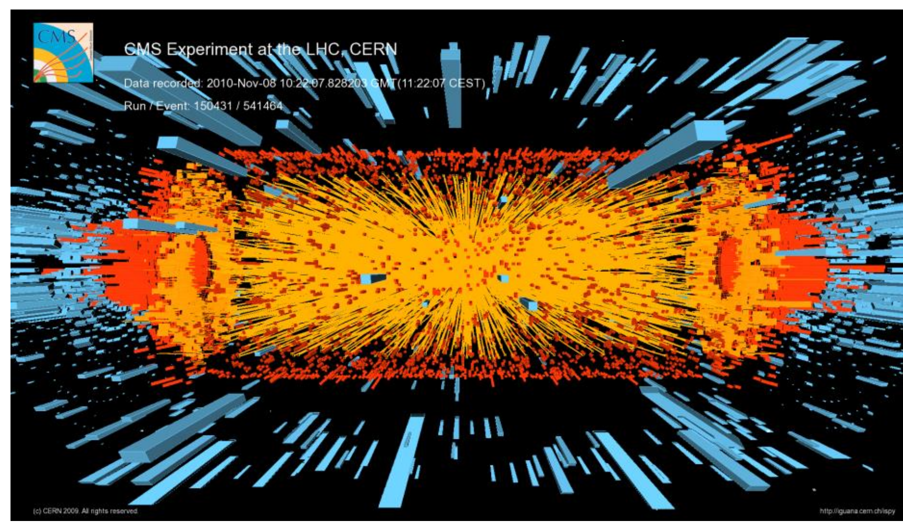




Heating up the matter with relativistic heavy-ion collisions

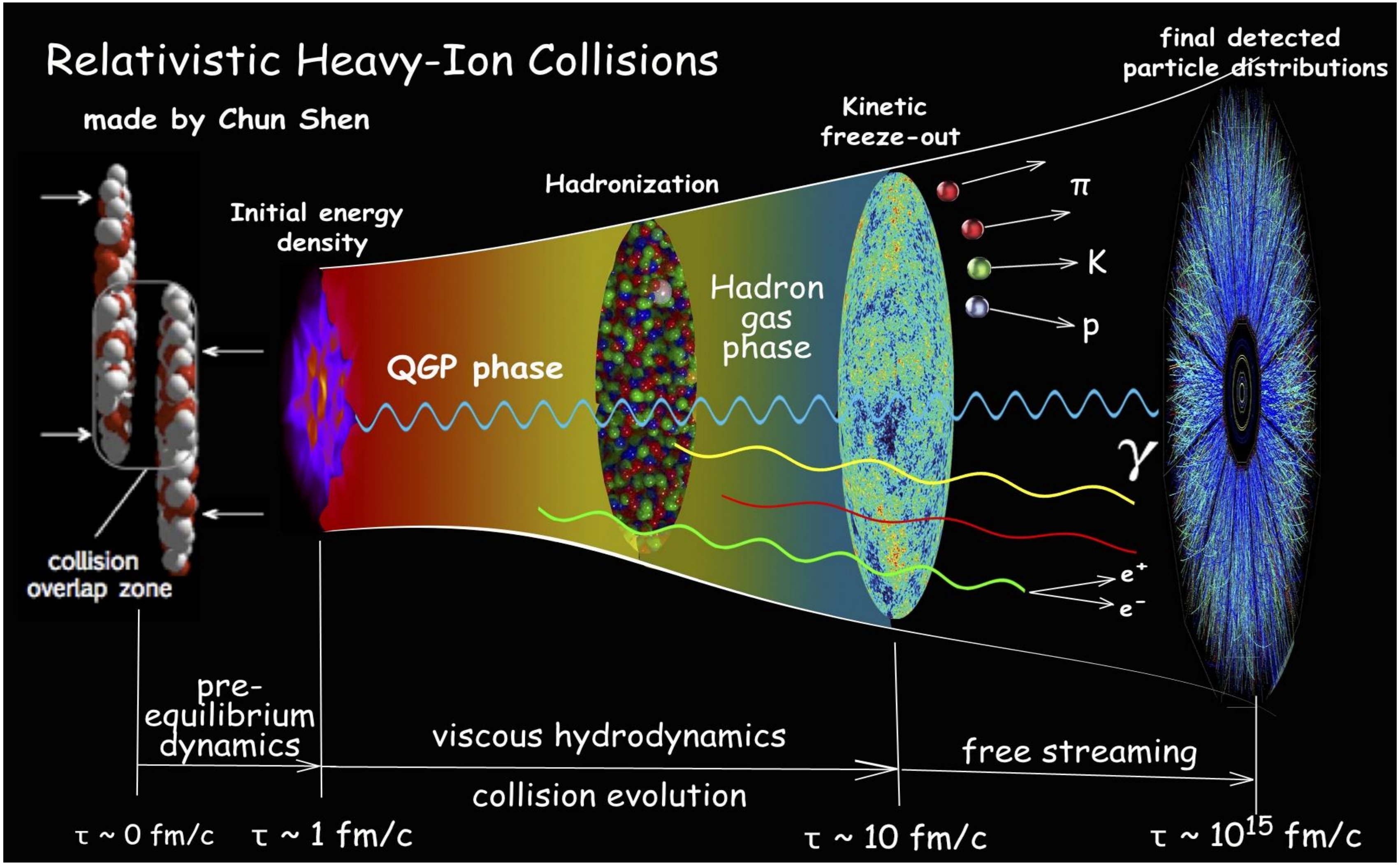




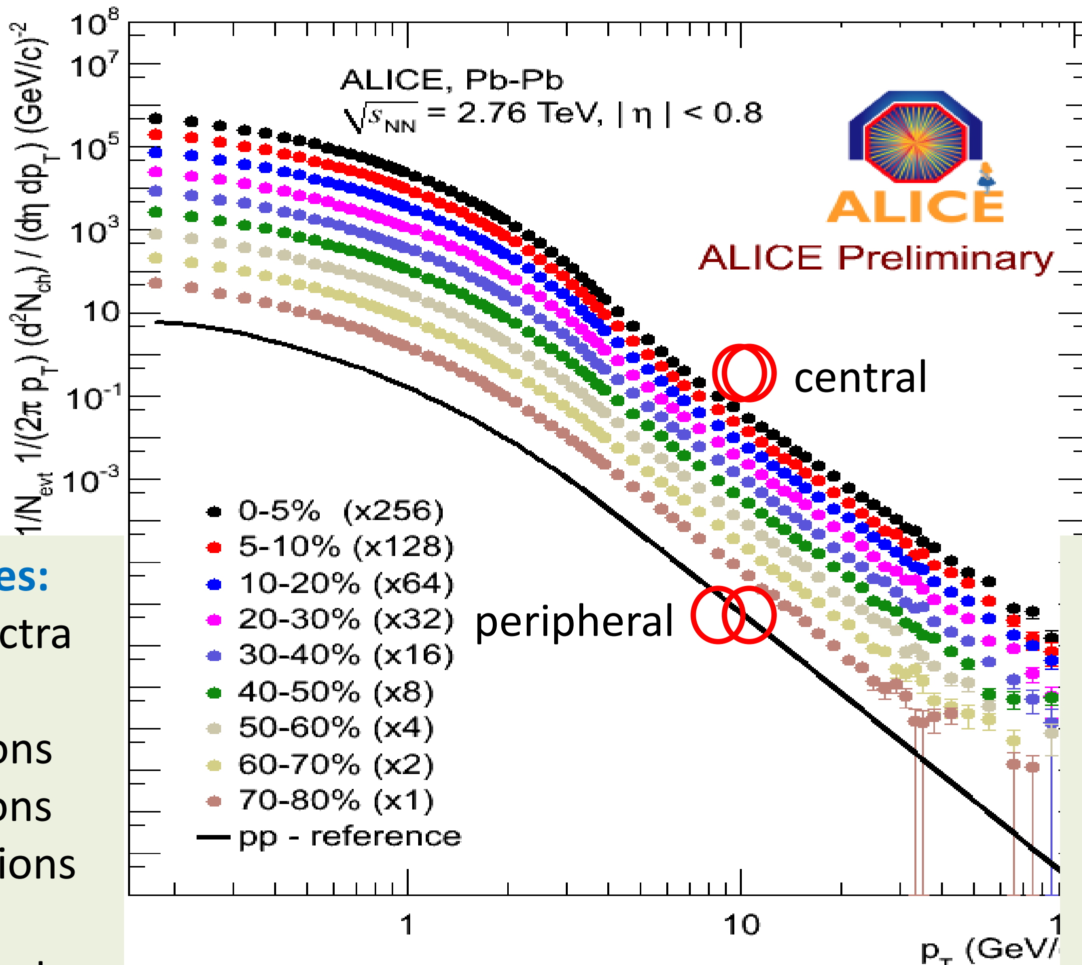


T. D. Lee, "A possible new form of matter", AIP Conf.Proc. 28 (1976) 65-81

"Standard Model" of RHIC & LHC heavy-ion collisions



Probes of QGP in heavy-ion collisions



Soft Probes:

Yields/Spectra

Flows

Fluctuations

Correlations

Decorrelations

…

“Internal” probes

Hard Probes:

Jets

Large p_T hadrons

Heavy quark/hadrons

Quarkonia

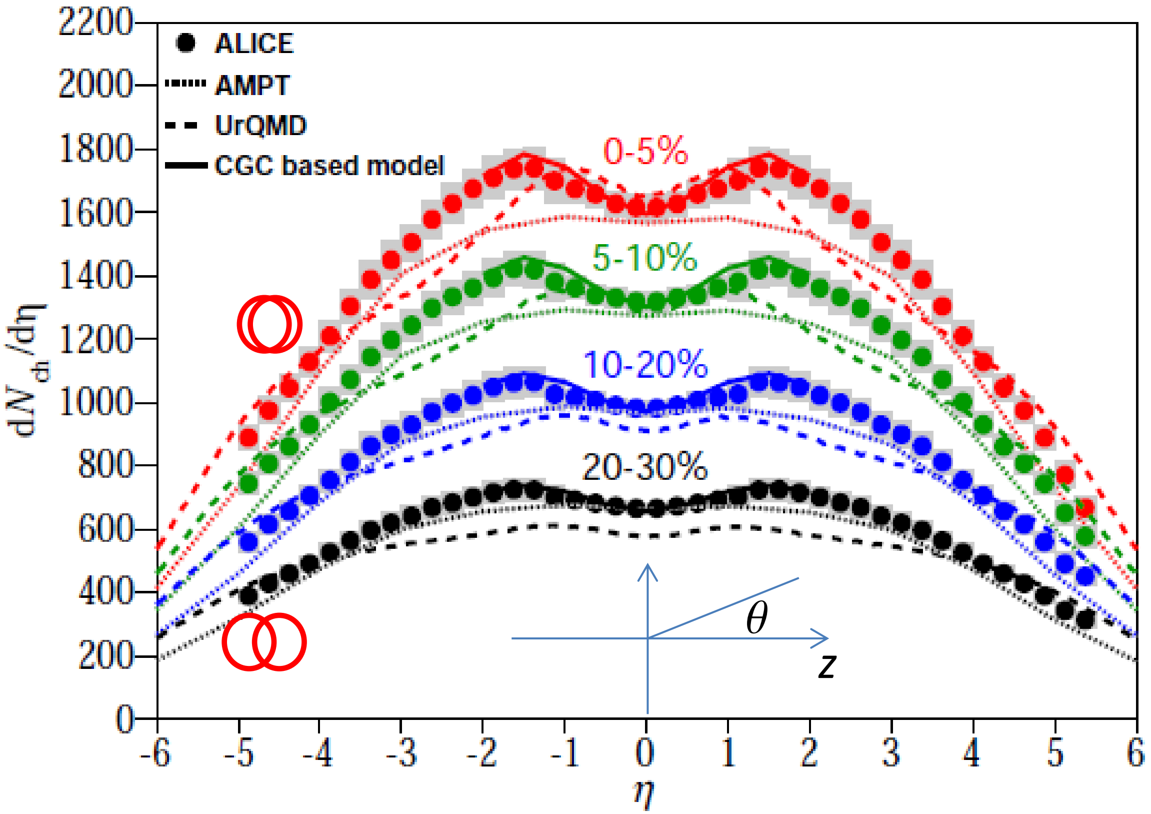
EM probes

…

“External” probes

Flow and collective properties

Particle distribution in longitudinal direction



$$\eta = \frac{1}{2}\ln\left(\frac{p + p_z}{p - p_z}\right) = -\ln\left(\tanh\frac{\theta}{2}\right)$$

$$LHC : \frac{dN_{ch}}{d\eta} = 1600$$

$$RHIC : \frac{dN_{ch}}{d\eta} = 700$$

$$LHC : \varepsilon_0 = 16GeV / fm^3$$

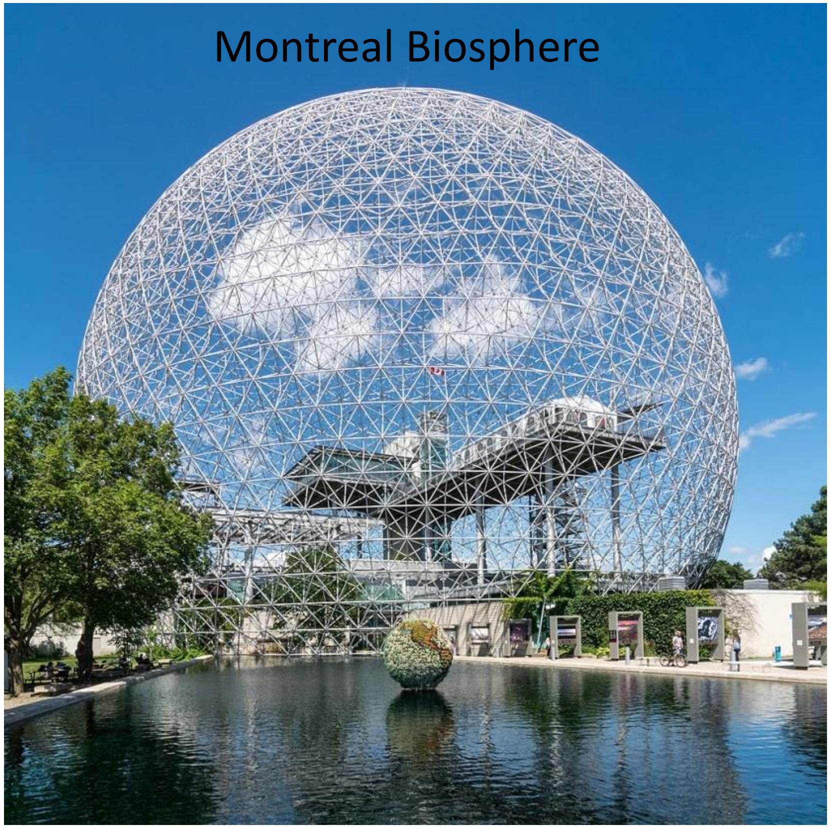
$$RHIC : \varepsilon_0 = 7GeV / fm^3$$

$$\varepsilon_0 = \frac{dE_T}{d\eta}\frac{1}{\tau_0 \pi R^2} = \frac{3}{2}\left\langle\frac{E_T}{N}\right\rangle\frac{dN_{ch}}{d\eta}\frac{1}{\tau_0 \pi R^2}$$

$$T_c = 155MeV$$

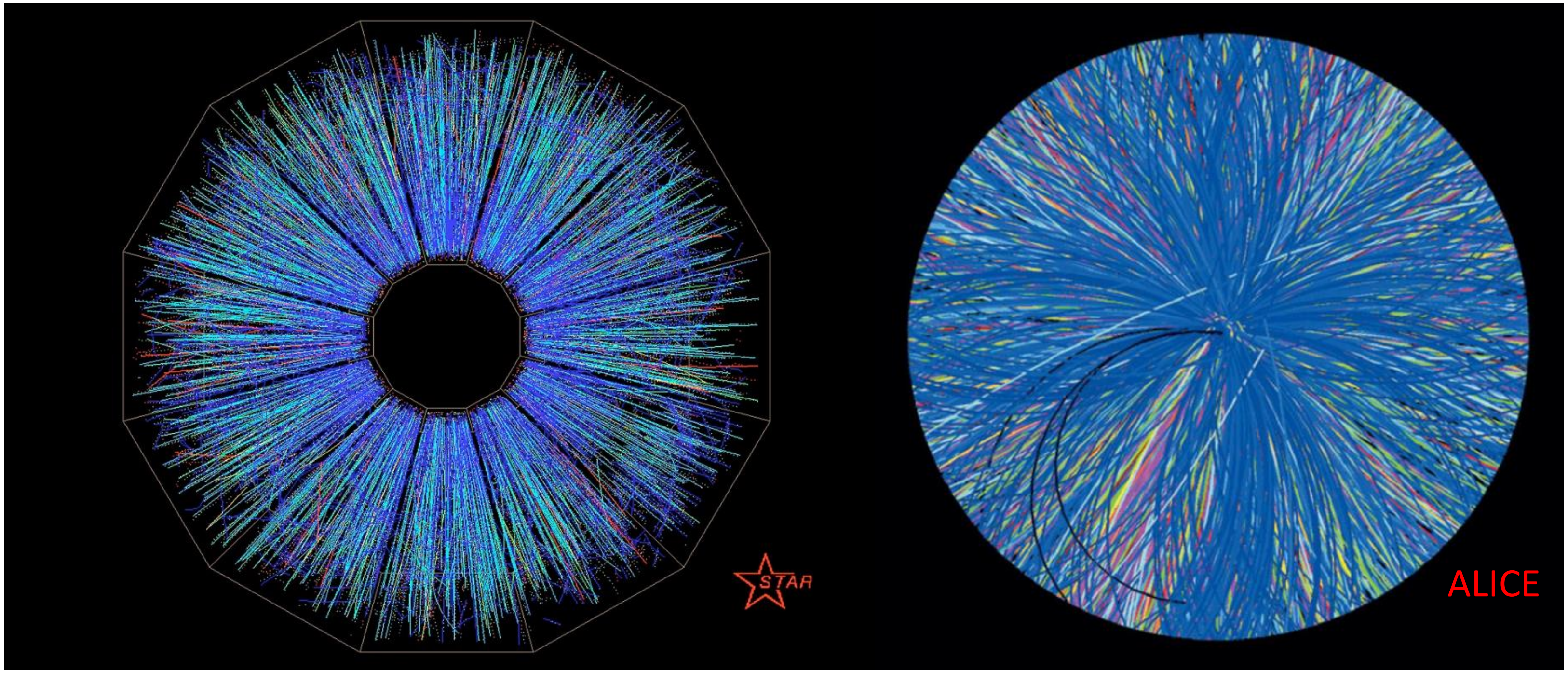
$$\varepsilon_c = 0.5GeV / fm^3$$

How high density?



$$\frac{6*10^{24}\mathrm{kg}*(3*10^{8}m/s)^{2}}{\frac{4}{3}\pi(38m)^{3}} = 2.3*10^{36}\frac{J}{m^{3}} = 2.3*10^{36}*\frac{10^{-9}GeV/(1.6*10^{-19})}{(10^{15}\mathrm{fm})^{3}} = 15\frac{GeV}{fm^{3}}$$

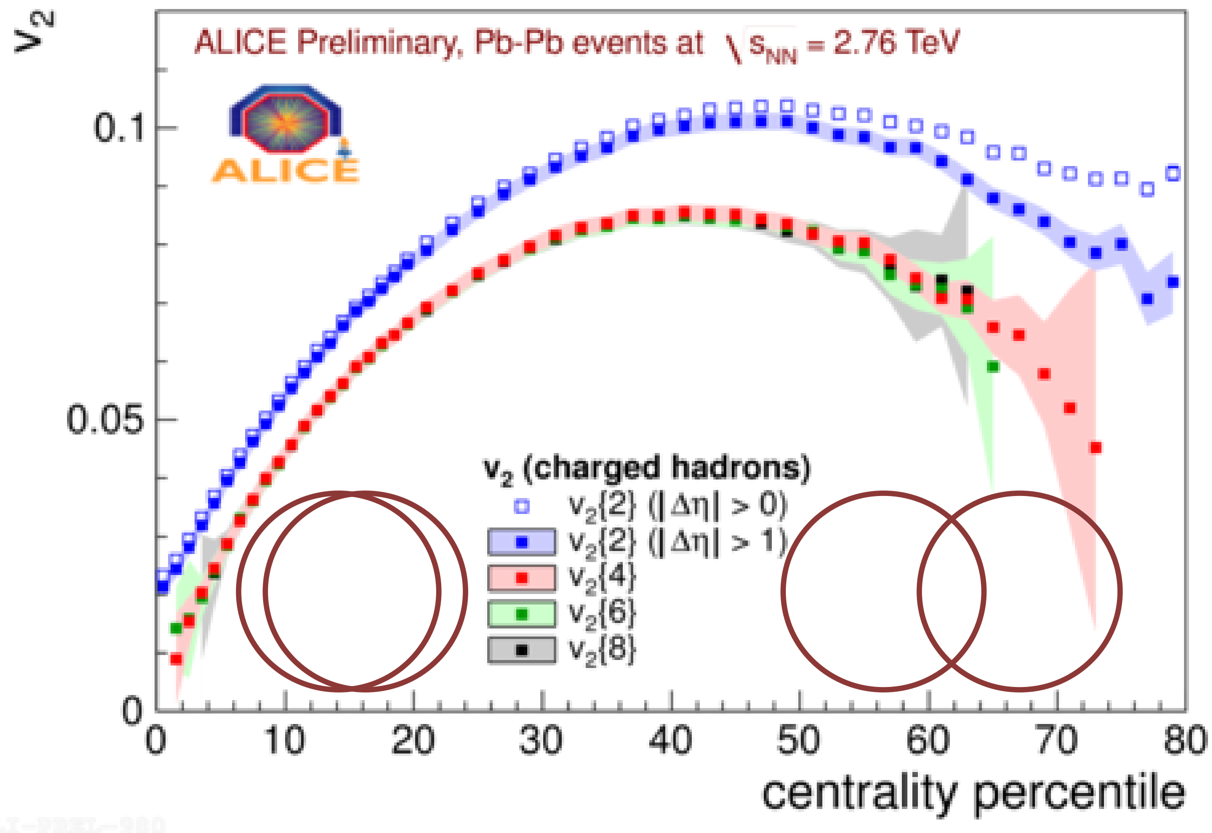
Particle distribution in transverse plane



- Particle production is not azimuthally symmetric.
- The azimuthal anisotropy can be analyzed by Fourier decomposition:

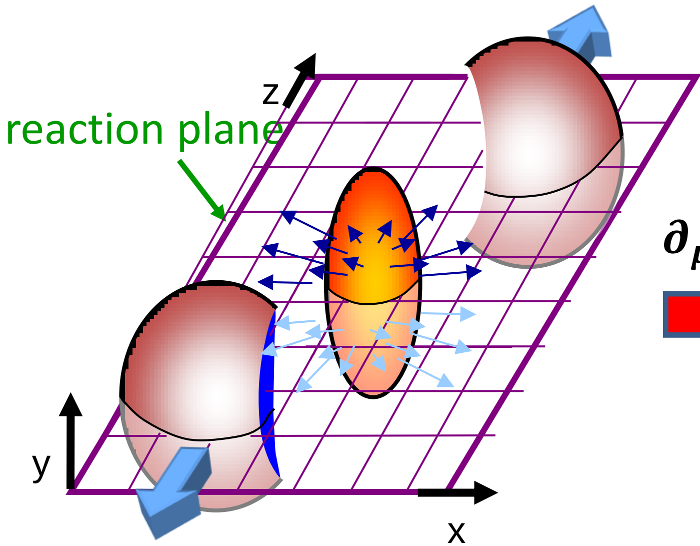
$$\frac{dN}{d\varphi} \propto 1 + \sum_n 2v_n \cos\left[n\left(\varphi - \Psi_n\right)\right]$$

Elliptic flow v_2 depends on collision geometry

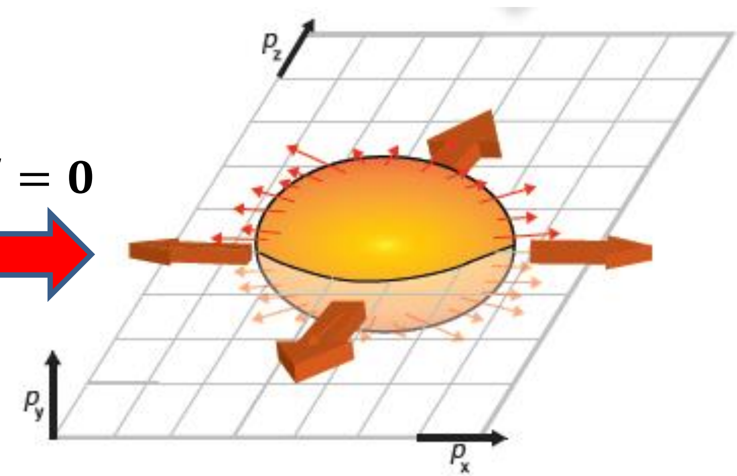


- Strong elliptic flows depending on collision centrality (system size & geometry)

The origin of elliptic flow



$\partial_\mu T^{\mu\nu} = 0$

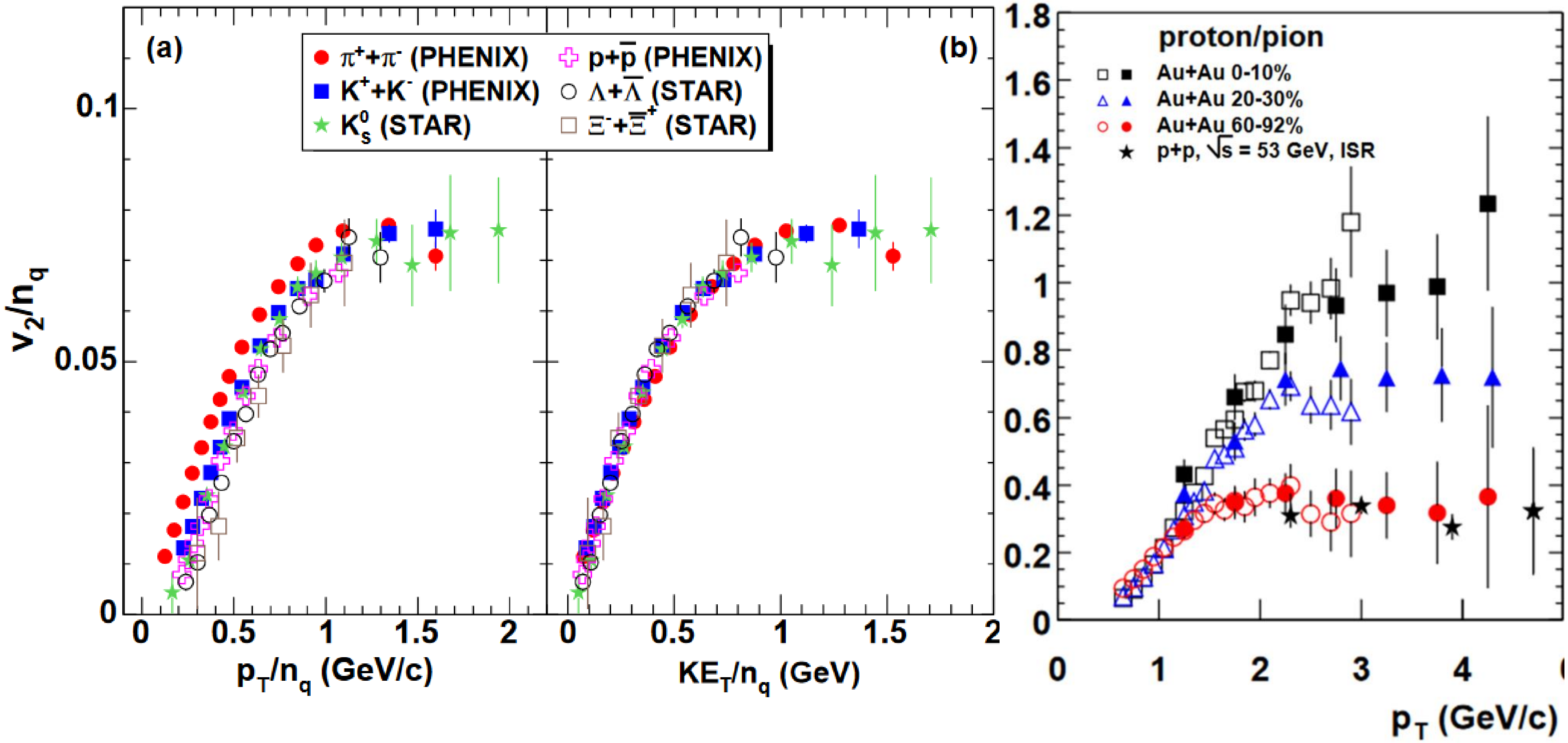


eccentricity $\varepsilon_2 = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$

elliptic flow $v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$

- **Relativistic hydrodynamics: the interaction among QGP constituents translates initial geometric anisotropy to final state momentum anisotropy.**
- **=> QGP is a strongly-coupled fluid**

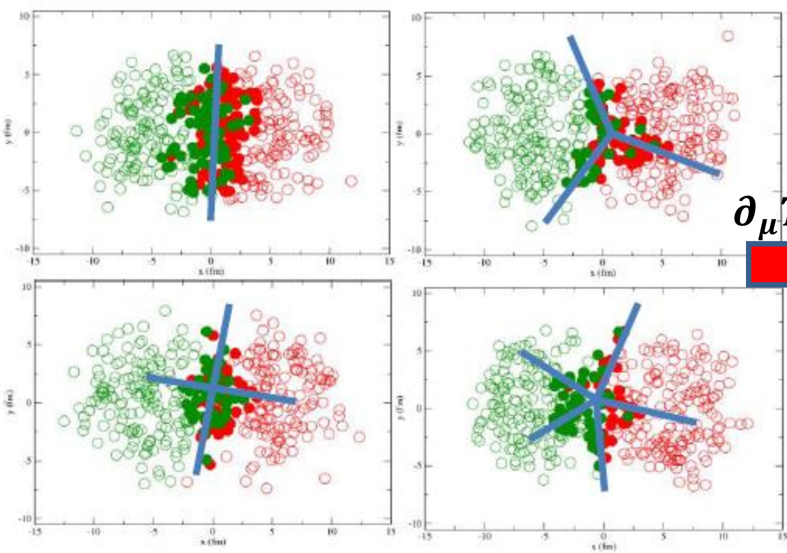
Number of constituent quark (NSQ) scaling



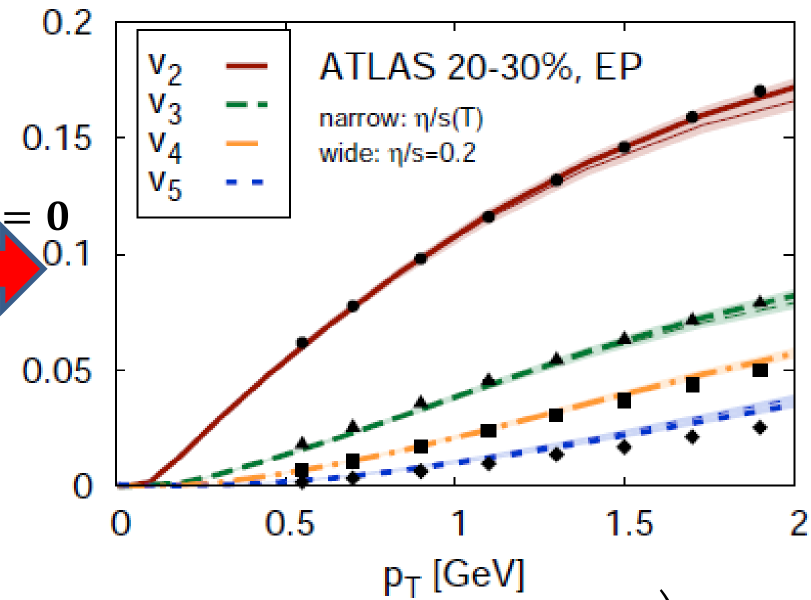
Coalescence of thermal partons from QGP can naturally explain the NSQ scaling of v_2 and the enhancement of baryon-to-meson ratio at intermediate p_T.

Initial-state fluctuations and final-state flows

- **Event-by-event initial state density and geometry fluctuations are translated into final state anisotropic flows via hydrodynamic evolution.**



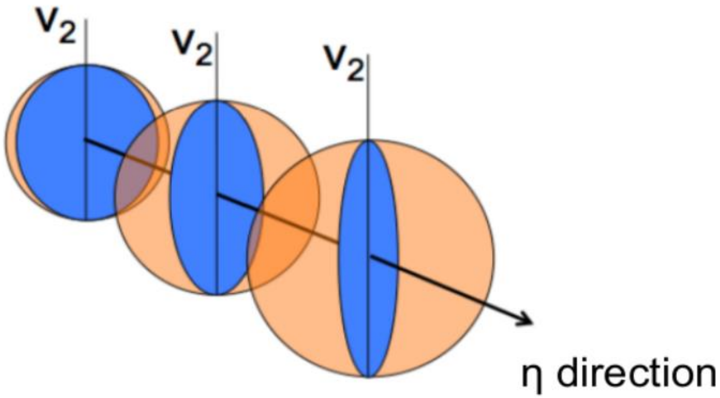
$\partial_\mu T^{\mu\nu} = 0$

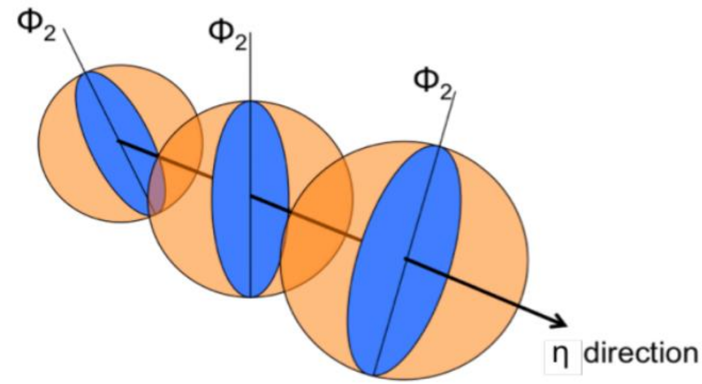


$$\frac{dN}{p_T dp_T dy d\phi} = \frac{dN}{2\pi p_T dp_T dy}\left(1 + \sum_n 2v_n(p_T, y)\cos\{n[\phi - \Psi_n(p_T, y)]\}\right)$$

Alver and Roland, PRC 2010; GYQ, Petersen, Bass, Muller, PRC 2010; Staig, Shuryak, PRC 2011; Teaney, Yan, PRC 2011; Gale, Jeon, Schenke, Tribedy, Venugopalan, PRL 2012; etc.

Longitudinal fluctuations and decorrelations

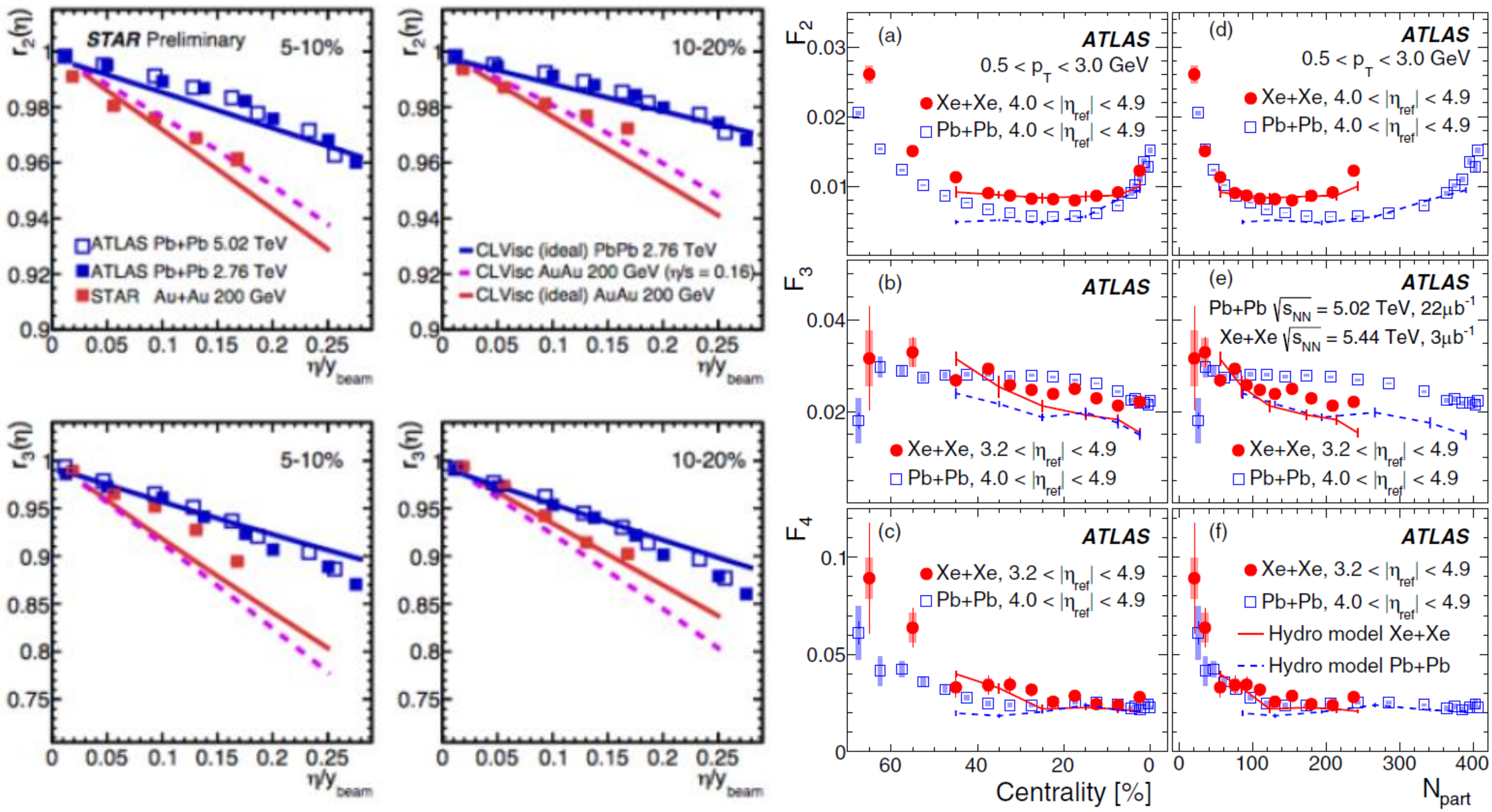




$$r_{n,k}(\eta|\eta_r) = \frac{\langle Q_n^k(\eta) Q_n^{*k}(-\eta_r)\rangle}{\langle Q_n^k(-\eta) Q_n^{*k}(-\eta_r)\rangle} \qquad r_{n,k}(\eta|\eta_r) = 1 - 2F_{n,k}\eta + \cdots$$

Petersen, Bhattacharya, Bass, Greiner, PRC 2011; Xiao, Liu, Wang, PRC 2013; Pang, GYQ, Roy, Wang, Ma, PRC 2015; Pang, Petersen, GYQ, Roy, Wang, EPJA 2016; Jia, Huo, PRC 2014; CMS, PRC 2015; Jia et al, JPG 2017; ATLAS EPJC 2018; Bozek, Broniowski, PRC 2018; Wu, Pang, GYQ, Wang, PRC 2018; etc.

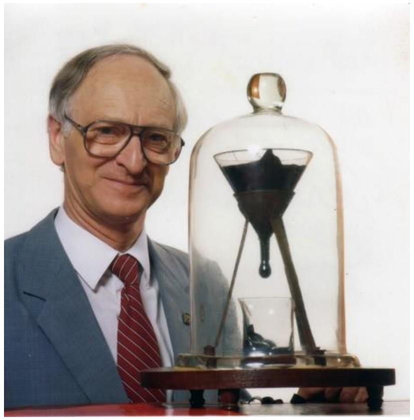
Longitudinal decorrelations in different collision energies and systems



Pang, GYQ, Roy, Wang, Ma, PRC 2015; Pang, Petersen, GYQ, Roy, Wang, EPJA 2016; Wu, Pang, GYQ, Wang, PRC 2018

Fluidity

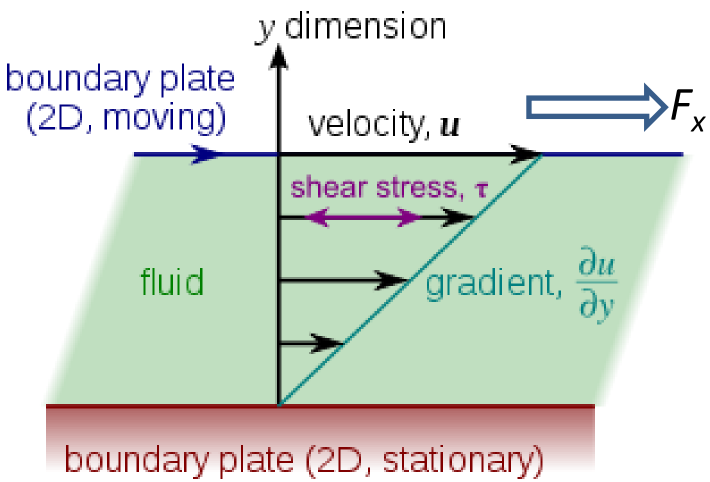
  

- How the fluid flows depends on its **viscosity**.

Shear viscosity

- Shear viscosity η measures the resistance to shear flow.



$$\frac{F_x}{A_y} = \eta \frac{\partial u_x}{\partial y}$$

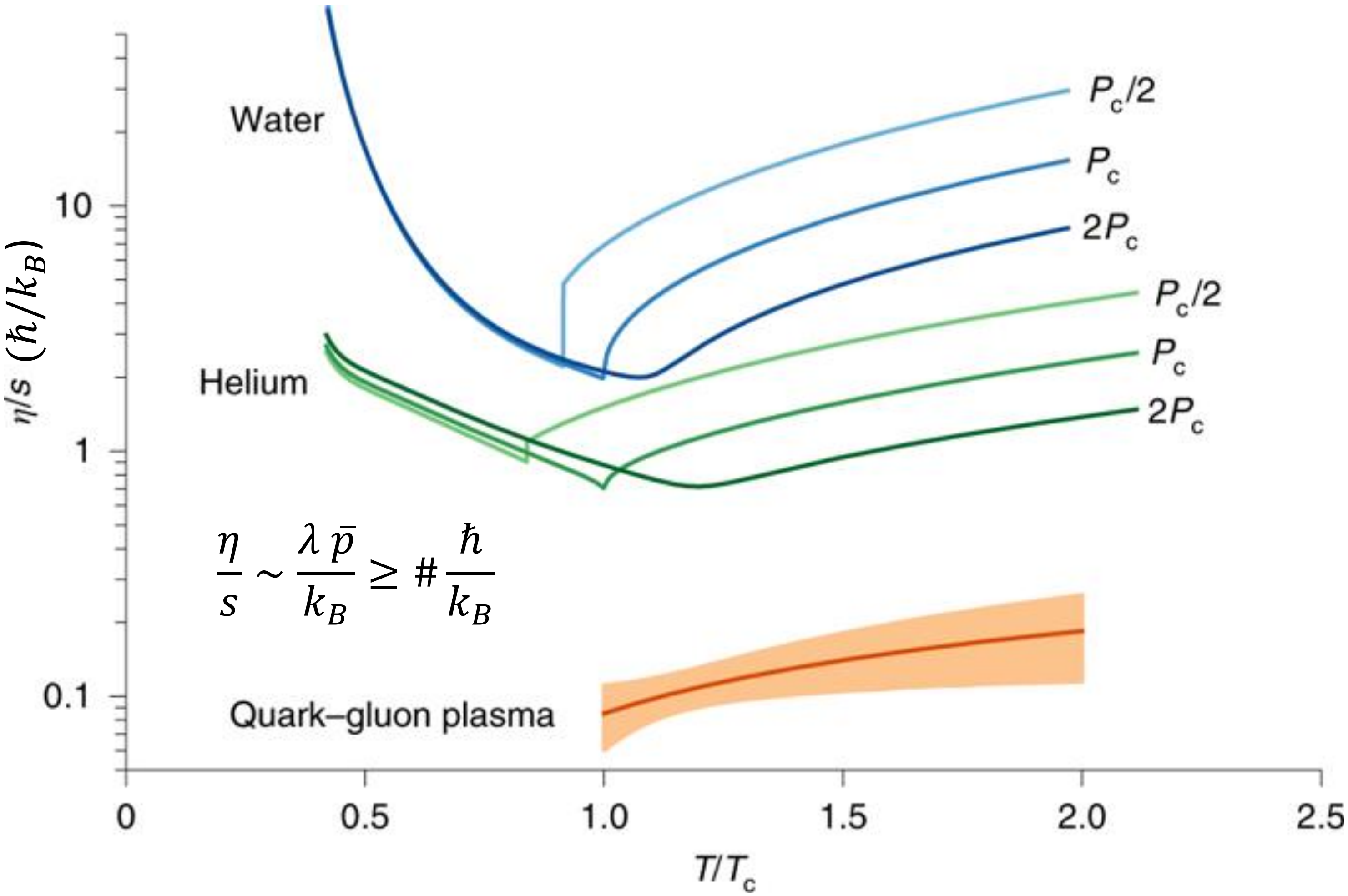
- Shear viscosity η measures the ability of momentum transport between different parts of the system.
- From kinetic theory, it is related to the strength of the interactions among the constituents of the system.

$$\eta \approx \frac{1}{3} n\lambda\overline{p}$$

Viscosities of some fluids

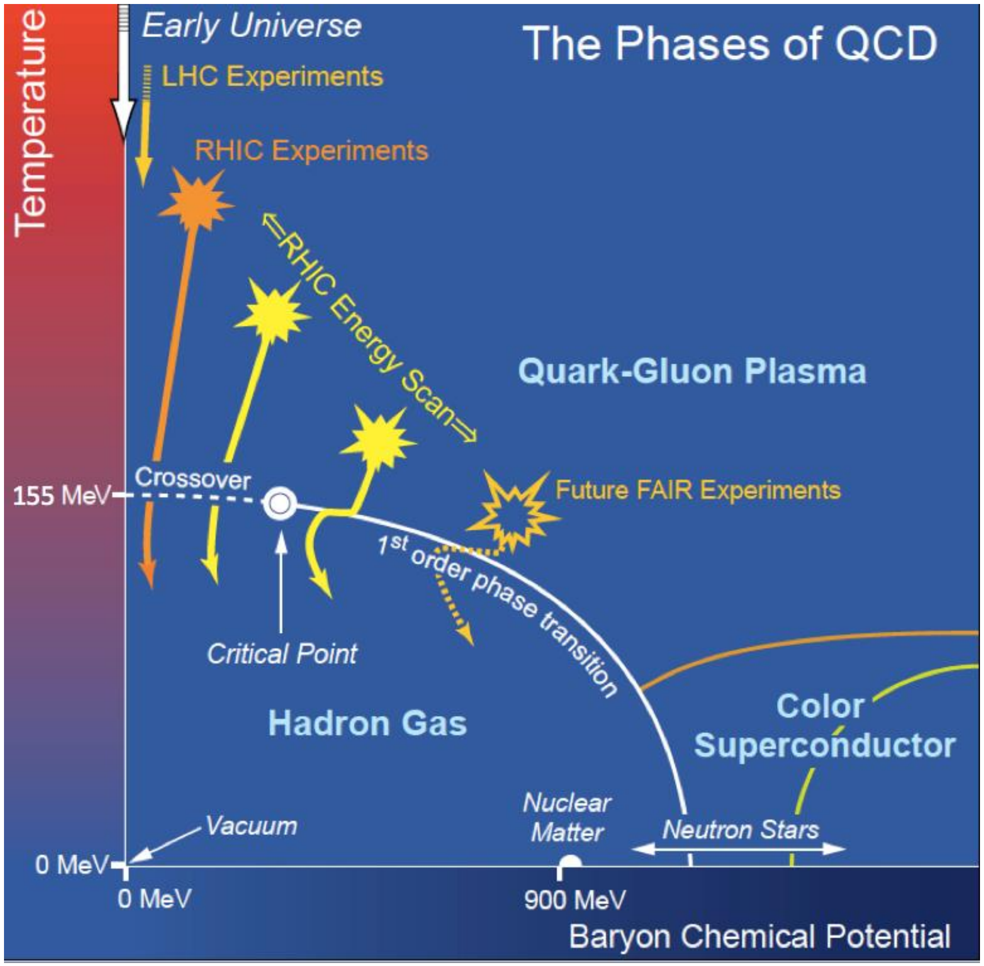
Fluid	viscosity（Pa*s）
Air	$1.8*10^{-5}$
Water	$8.9*10^{-4}$
Milk	$1.8*10^{-3}$
Olive Oil	0.04
Honey	10
Peanut Butter	250
Pitch	$2*10^{8}$
Quark-Gluon Plasma	???

Most perfect liquid



Bernhard, Moreland, Bass, Nature Physics 2019

Phases of strong-interaction matter



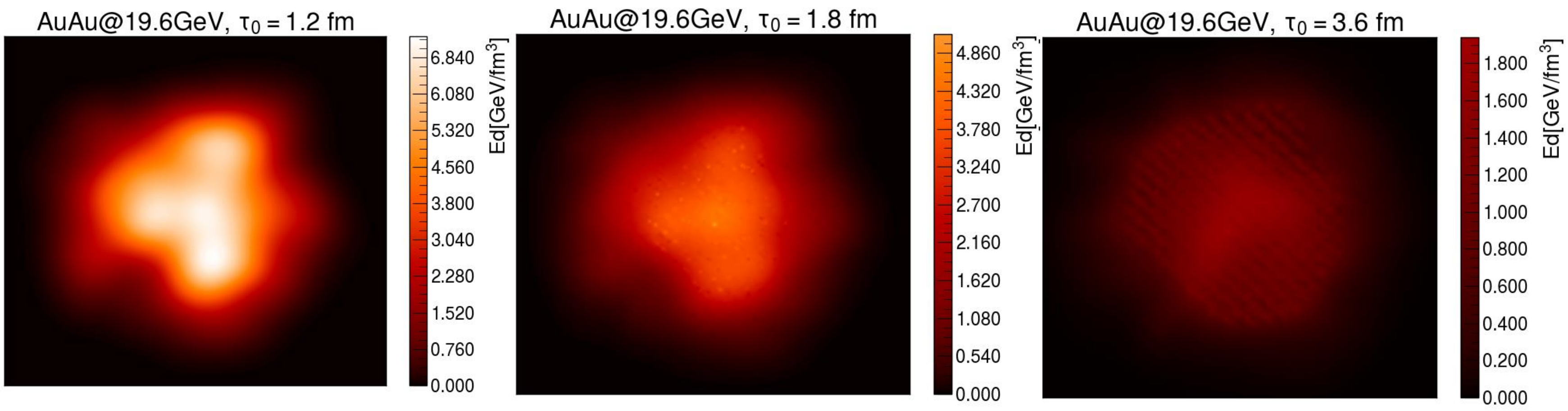
- Low T & μ_B => hadrons (**hadron matter**)
- T_c=155MeV => hadron matter melts into **quark-gluon plasma**
- Very high T => **early Universe**.
- QGP can be obtained by colliding two nuclei at extremely high energies (**relativistic heavy-ion collisions**)
- As E_{cm} increases, S increases, N_B is unchanged, S/N_B, s/n_B & T/μ_B increase

CLvisc (3+1)-D hydrodynamics for BES energies

$$\nabla_\mu T^{\mu\nu} = \nabla_\mu(eU^\mu U^\nu - P\Delta^{\mu\nu} + \pi^{\mu\nu}) = 0;\ \nabla_\mu J^\mu = \nabla_\mu(nU^\mu + V^\mu) = 0$$

$$\Delta^{\mu\nu}_{\alpha\beta} D\pi^{\alpha\beta} = -\frac{1}{\tau_\pi}(\pi^{\mu\nu} - \eta_\nu\sigma^{\mu\nu}) - \frac{4}{3}\pi^{\mu\nu}\theta - \frac{5}{7}\pi^{\alpha<\mu}\sigma_\alpha^{\nu>} + \frac{9}{70}\frac{4}{e+P}\pi^{\alpha<\mu}\pi_\alpha^{\nu>};$$

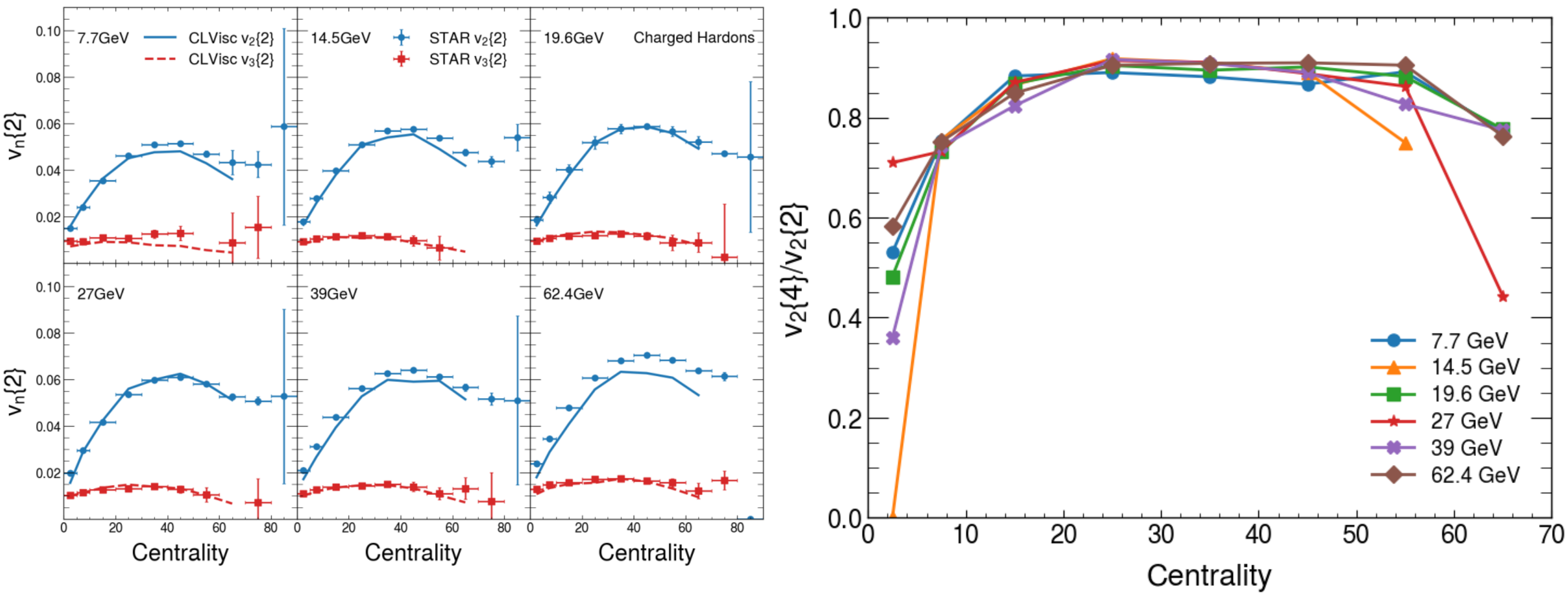
$$\Delta^{\mu\nu} DV_\nu = -\frac{1}{\tau_V}(V^\mu - \kappa_B\nabla^\mu\frac{\mu}{T}) - V^\mu\theta - \frac{3}{10}V_\nu\sigma^{\mu\nu}$$



(3+1)-dimensional relativistic viscous hydrodynamics model CLVisc2.0 includes baryon conservation and Israel-Stewart-like diffusion, NEOS-BQS equation of state, EbE initial conditions, SMASH hadron cascade.

Wu, GYQ, Pang, Wang, 2107.04949

CLvisc (3+1)-D hydrodynamics for BES energies



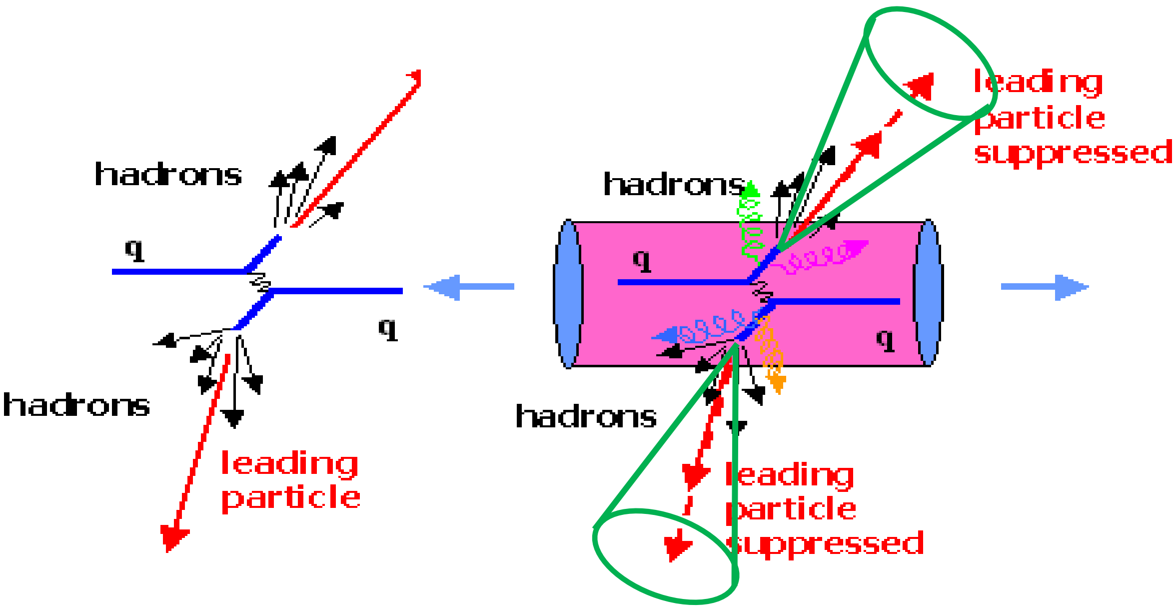
CLVisc2.0 can provide a good description of identified particle spectra, mean transverse momenta and anisotropic flows for different centralities and over a wide range of collision energies (7.7-62.4 GeV).

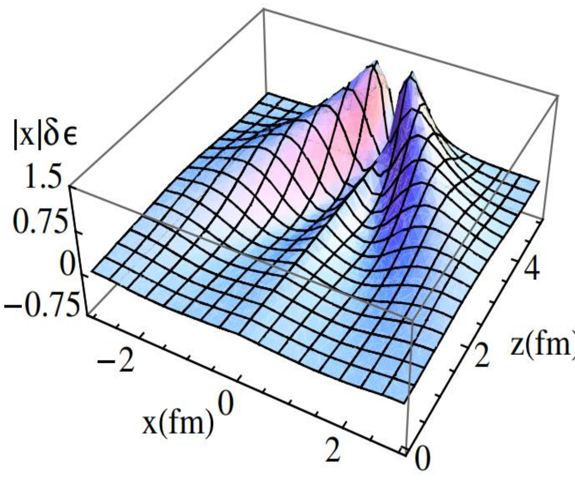
The relative fluctuations of v_2 are not sensitive to collision energies, which indicates that the flow fluctuations are mainly driven by initial states

Wu, GYQ, Pang, Wang, 2107.04949

Jets and jet-medium interaction

Jet quenching



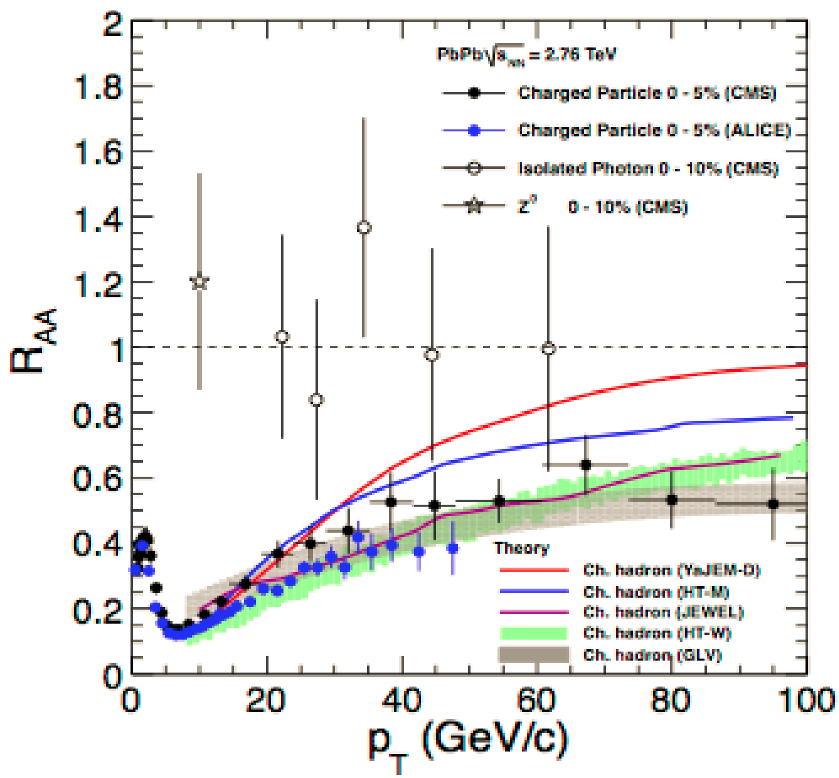


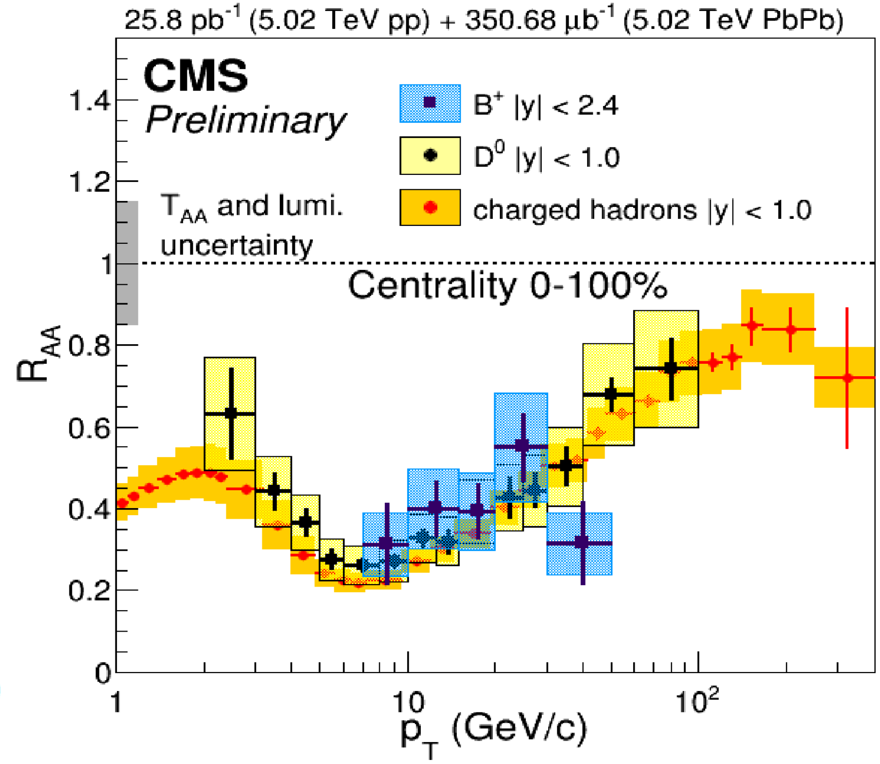
N+N

A+A: jet quenching

- **Jets and jet-medium interaction (jet quenching) provide valuable tools to probe hot & dense QGP in heavy-ion collisions (at RHIC & LHC):**
- **(1) jet energy loss (2) jet deflection and broadening (3) modification of jet structure/substructure (4) jet-induced medium excitation**

Nuclear modifications of large p_T hadrons
R_{AA} for different particles

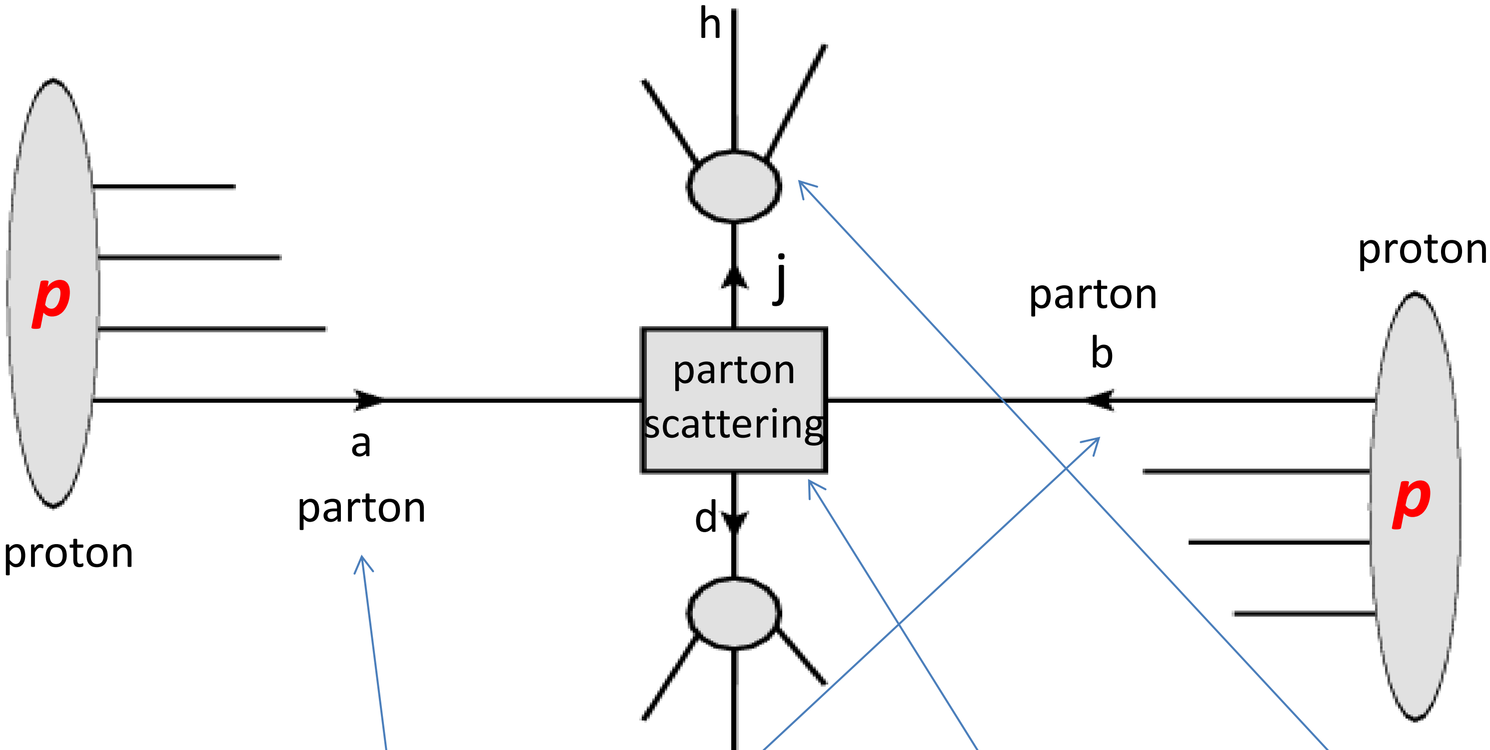




$$R_{AA} = \frac{1}{N_{\mathrm{coll}}} \frac{dN^{AA} / d^2 p_T dy}{dN^{pp} / d^2 p_T dy}$$

Color & flavor dependences of parton energy loss: $\Delta E_g > \Delta E_{uds} > \Delta E_c > \Delta E_b$?

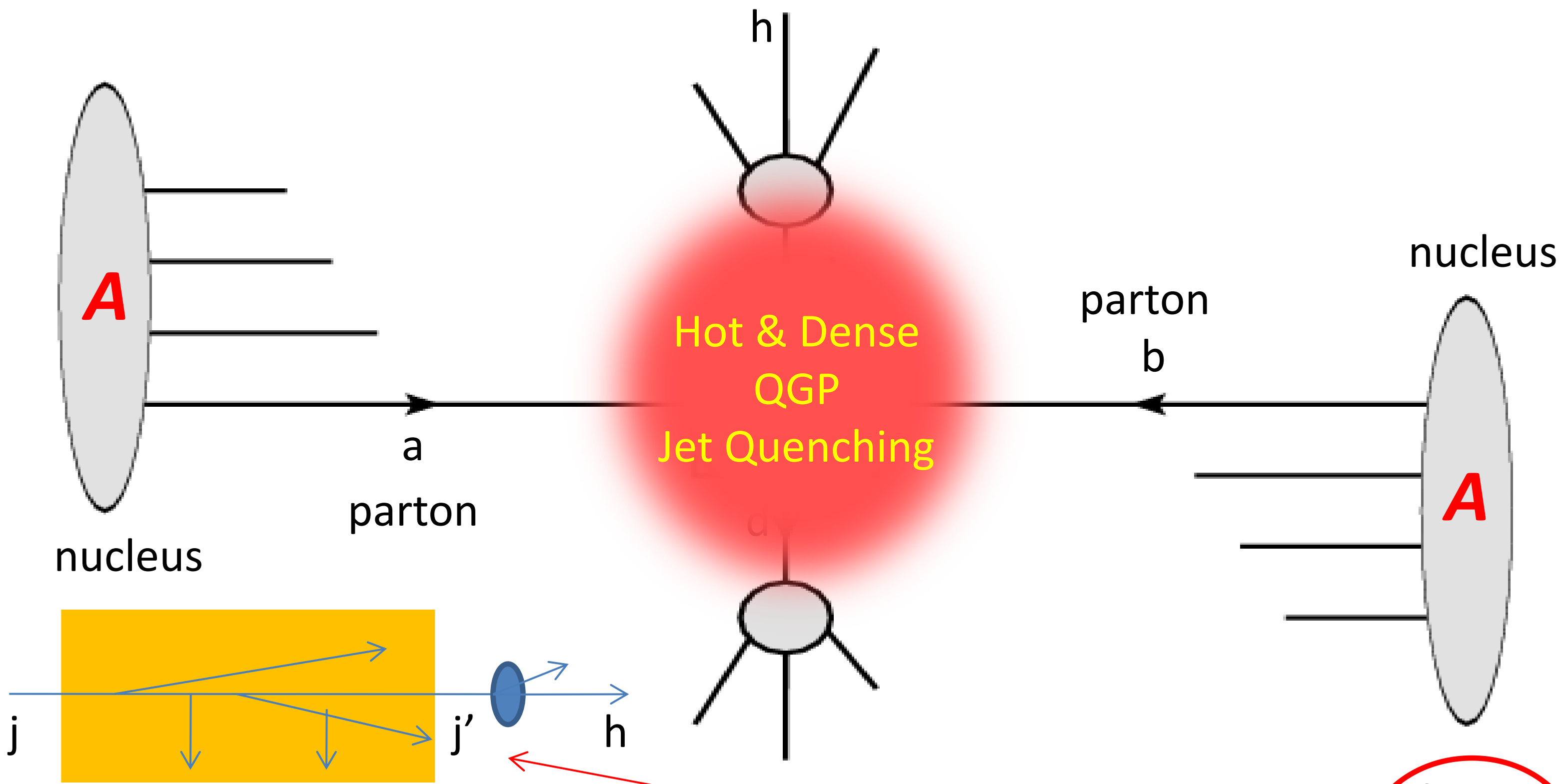
Leading hadron production in pp collisions



$$d\sigma_h = \sum_{abj} f_{a/A} \otimes f_{b/B} \otimes d\sigma_{ab\to jX} \otimes D_{h/j}$$

pQCD factorization: Large-p_T processes may be factorized into long-distance pieces in terms of PDF & FF, and short-distance parts describing hard interactions of partons.

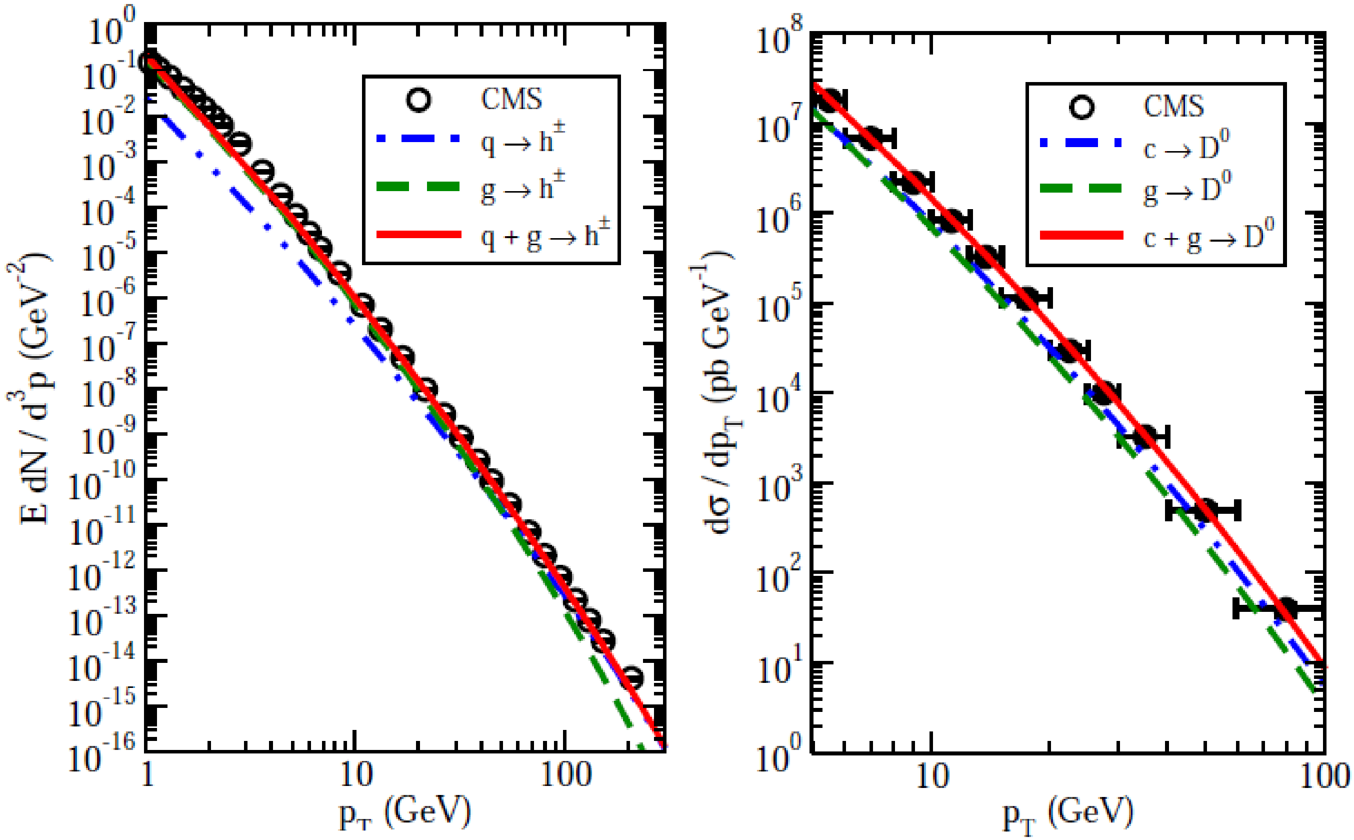
Leading hadron production in AA collisions



$$d\tilde{\sigma}_h = \sum_{abjX} f_{a/A} \otimes f_{b/B} \otimes d\sigma_{ab\to jX} \otimes \tilde{D}_{h/j}$$

$$d\tilde{\sigma}_h = \sum_{abjj'} f_a \otimes f_b \otimes d\sigma_{ab\to jX} \otimes P_{j\to j'} \otimes D_{h/j'}$$

Hadron productions in pp collisions @ NLO



$$d\sigma_{pp\to hX} = \sum_{abc} \int dx_a \int dx_b \int dz_c f_a(x_a) f_b(x_b)\, d\hat{\sigma}_{ab\to c} D_{h/c}(z_c)$$

Based on B. Jager, A. Schafer, M. Stratmann, and W. Vogelsang, Phys. Rev. D67, 054005 (2003)
F. Aversa, P. Chiappetta, M. Greco, and J. P. Guillet, Nucl. Phys. B327, 105 (1989).

Linear Boltzmann Transport (LBT) Model

- **Boltzmann equation:** $p_1 \cdot \partial f_1(x_1, p_1) = E_1 C[f_1]$
- **Elastic collisions:**

$$\Gamma_{12\to34} = \frac{\gamma_2}{2E_1}\int \frac{d^3p_2}{(2\pi)^3 2E_2}\int \frac{d^3p_3}{(2\pi)^3 2E_3}\int \frac{d^3p_4}{(2\pi)^3 2E_4}$$
$$\times f_2(\vec{p}_2)\left[1 \pm f_3(\vec{p}_1 - \vec{k})\right]\left[1 \pm f_4(\vec{p}_2 + \vec{k})\right]$$
$$\times (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - p_4)|\mathcal{M}_{12\to34}|^2$$

$$P_{el} = 1 - e^{-\Gamma_{el}\Delta t}$$

Matrix elements taken from LO pQCD

- **Inelastic collisions:**

$$\langle N_g \rangle = \Gamma_g \Delta t = \Delta t \int dx dk_\perp^2 \frac{dN_g}{dx dk_\perp^2 dt}$$

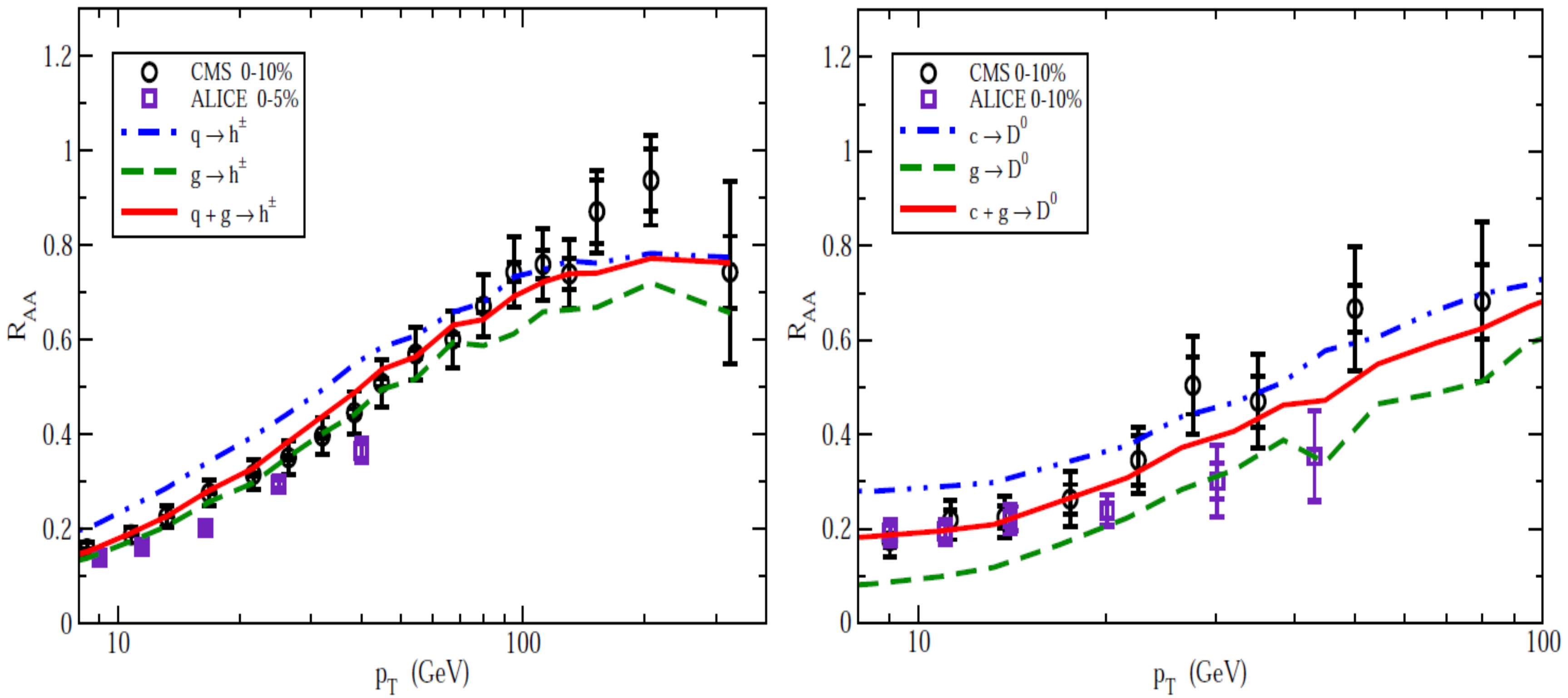
$$P_{inel} = 1 - e^{-\langle N_g \rangle}$$

Radiation spectra taken from higher-twist formalism: Guo, Wang PRL 2000; Zhang, Wang, Wang, PRL 2004; Zhang, Hou, GYQ, PRC 2019.

- **Elastic + Inelastic:** $P_{tot} = 1 - e^{-\Gamma_{tot}\Delta t} = P_{el} + P_{inel} - P_{el}P_{inel}$

He, Luo, Wang, Zhu, PRC 2015; Cao, Luo, GYQ, Wang, PRC 2016, PLB 2018; etc.

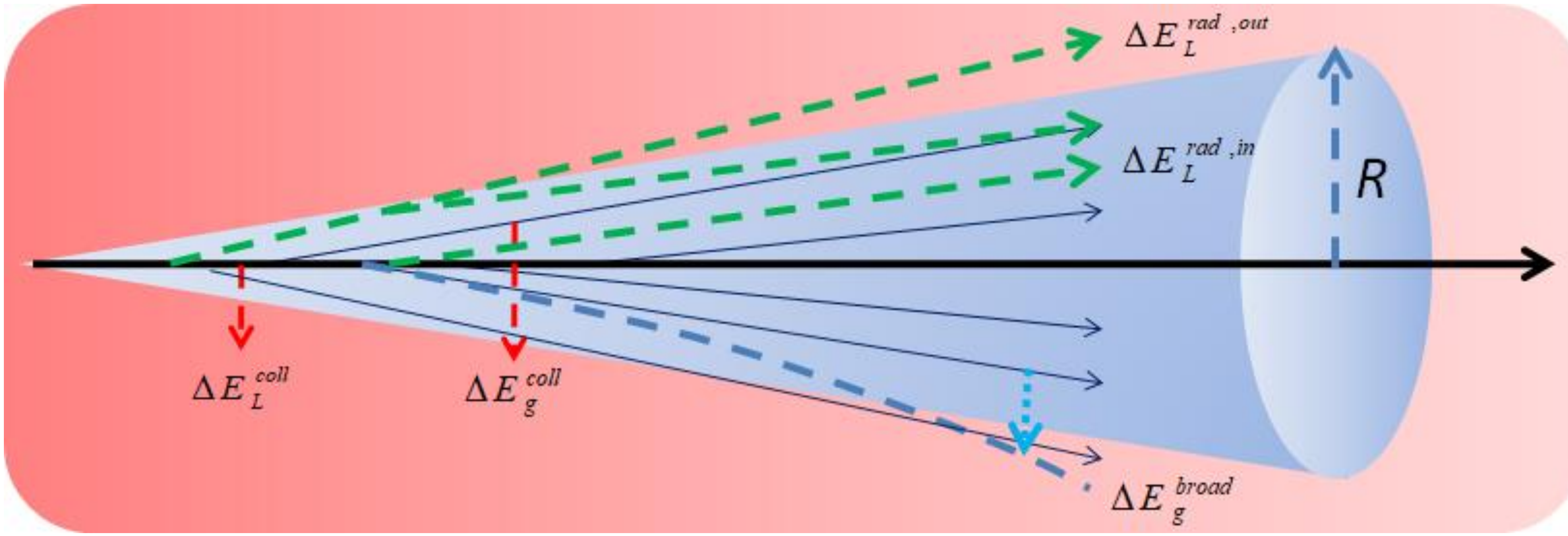
Flavor hierarchy of jet quenching



- **A state-of-art jet quenching framework (NLO-pQCD + LBT + Hydrodynamics)**
- **Quark-initiated hadrons have less quenching effects than gluon-initiated hadrons.**
- **Combining both quark and gluon contributions, we obtain a nice description of charged hadron & D & B meson R_{AA} over a wide range of p_T.**

Xing, Cao, GYQ, Xing, PLB 2020

Full jet evolution & energy loss in medium



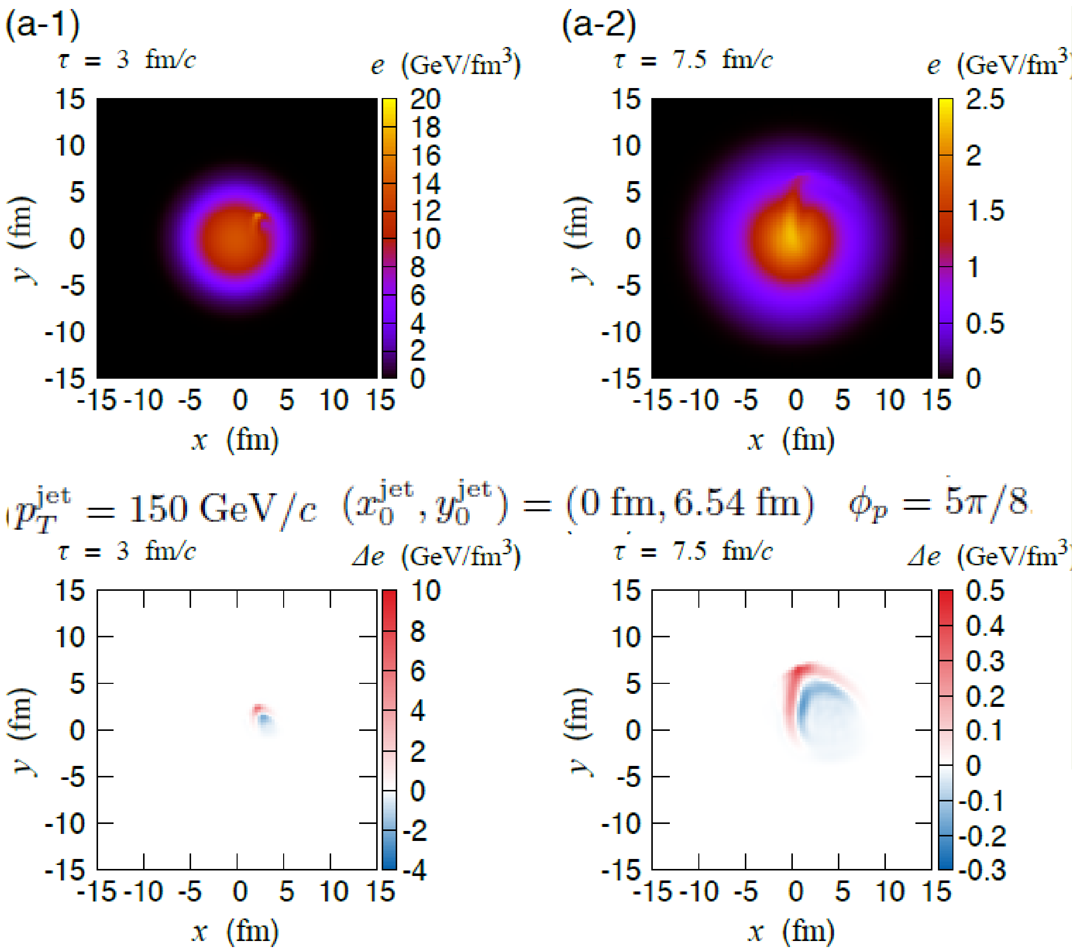
$$E_{jet} = E_{in} + E_{lost} = E_{in} + E_{rad,out} + E_{kick,out} + (E_{th} - E_{th,in})$$

Vitev, Zhang, PRL 2010; GYQ, Muller, PRL, 2011; Casalderrey-Solana, Milhano, Wiedemann, JPG 2011; Young, Schenke, Jeon, Gale, PRC, 2011; Dai, Vitev, Zhang, PRL 2013; Wang, Zhu, PRL 2013; Blaizot, Iancu, Mehtar-Tani, PRL 2013; etc.

Jet evolution & medium response

$$\frac{\partial f(\vec{p},t)}{\partial t} = C_{coll.E.loss}[f] + C_{broad}[f] + C_{rad}[f]$$

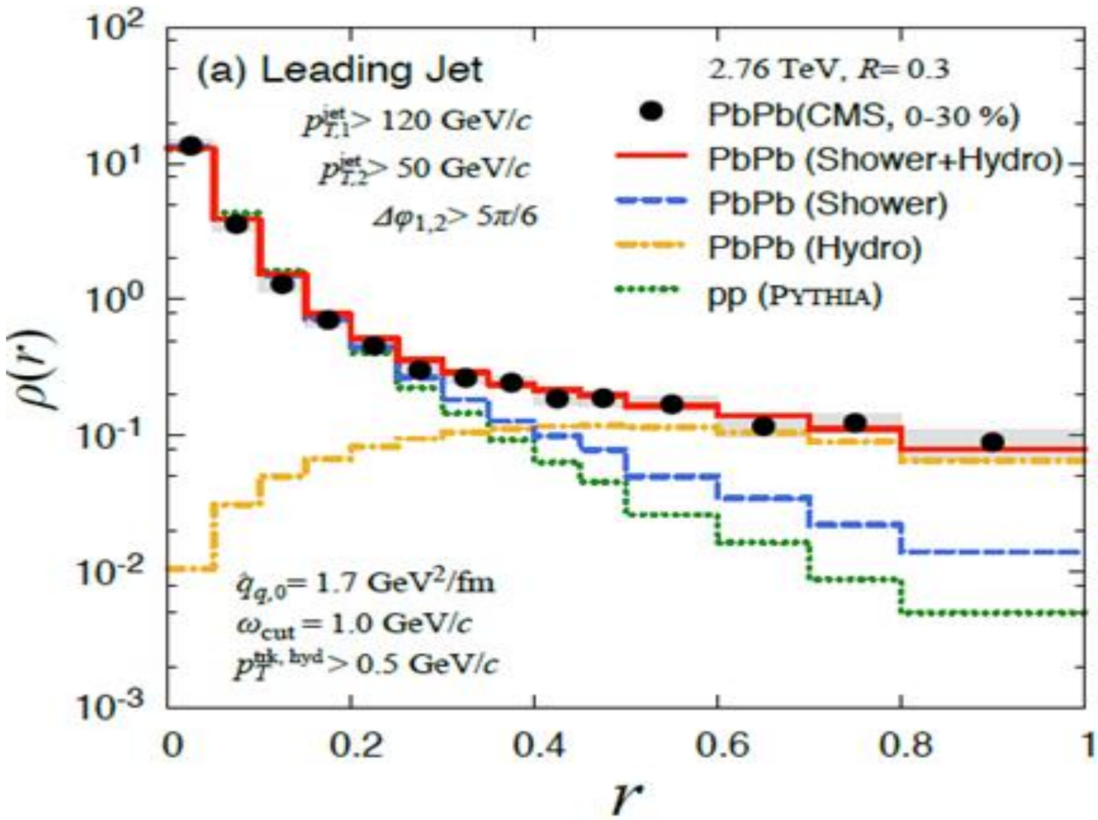
$$\partial_\mu T^{\mu\nu}_{\rm QGP}(x) = J^\nu(x) = -\partial_\mu T^{\mu\nu}_{\rm jet}(x) = -\frac{dP^\nu_{\rm jet}}{dt d^3x} = -\sum_j \int \frac{d^3k_j}{\omega_j} k^\nu_j k^\mu_j \partial_\mu f_j(\boldsymbol{k}_j, \boldsymbol{x}, t)$$

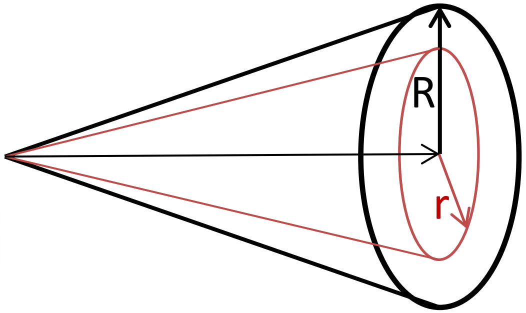


- **V-shaped wave fronts are induced by the jet, and develop with time**
- **The wave fronts carry the energy & momentum, propagates outward & lowers energy density behind the jet**
- **Jet-induced flow and the radial flow of the medium are pushed and distorted by each other**

Chang, GYQ, PRC 2016
Tachibana, Chang, GYQ, PRC 2017
Chang, Tachibana, GYQ, PLB 2020

Signal of jet-induced flow in jet shape



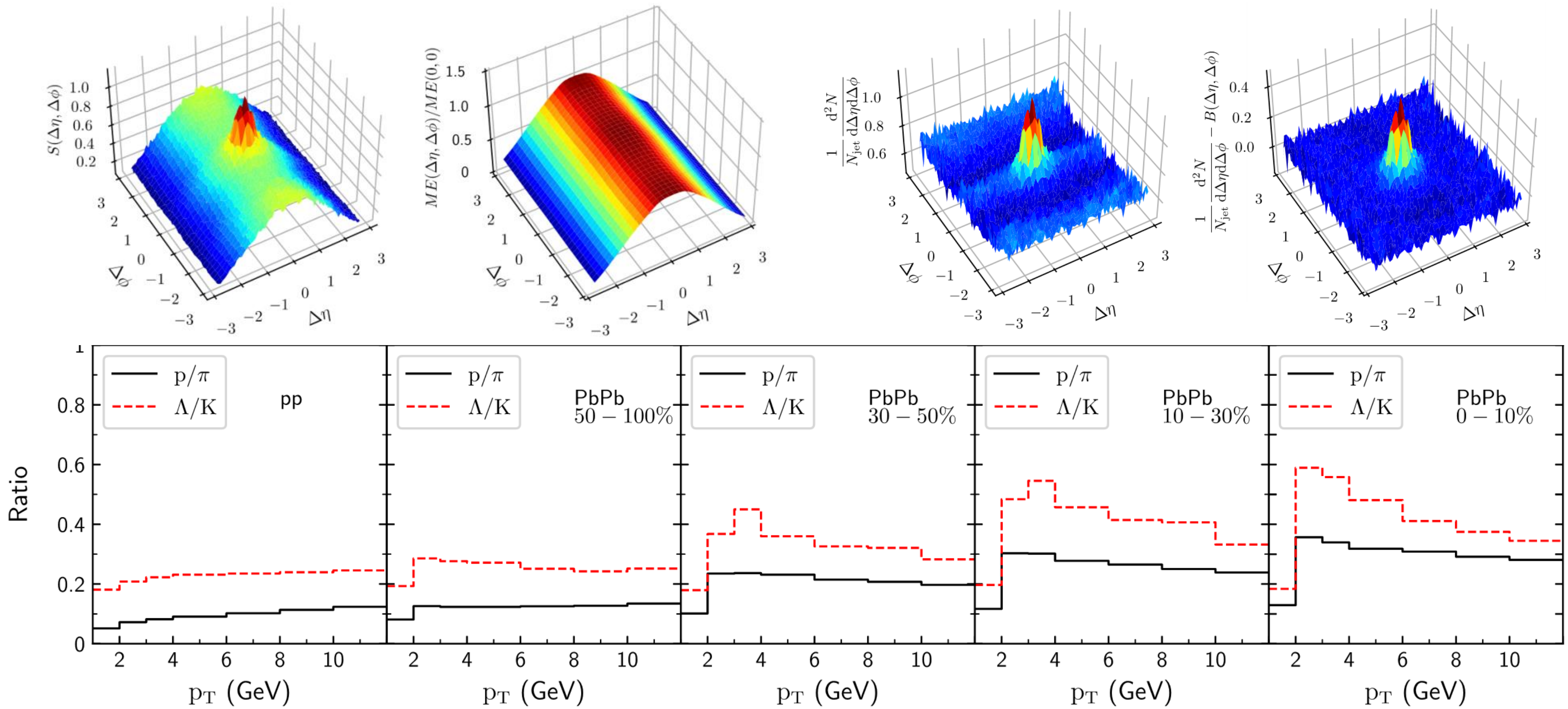


The contribution from the hydro part is quite flat and finally dominates over the shower part in the region from r = 0.4-0.5.

Signal of jet-induced medium excitation in full jet shape at large r.

Chang, GYQ, PRC 2016; Tachibana, Chang, GYQ, PRC 2017; Chang, Tachibana, GYQ, PLB 2020

Enhancement of baryon-to-meson ratios around the jet as a signature of medium response



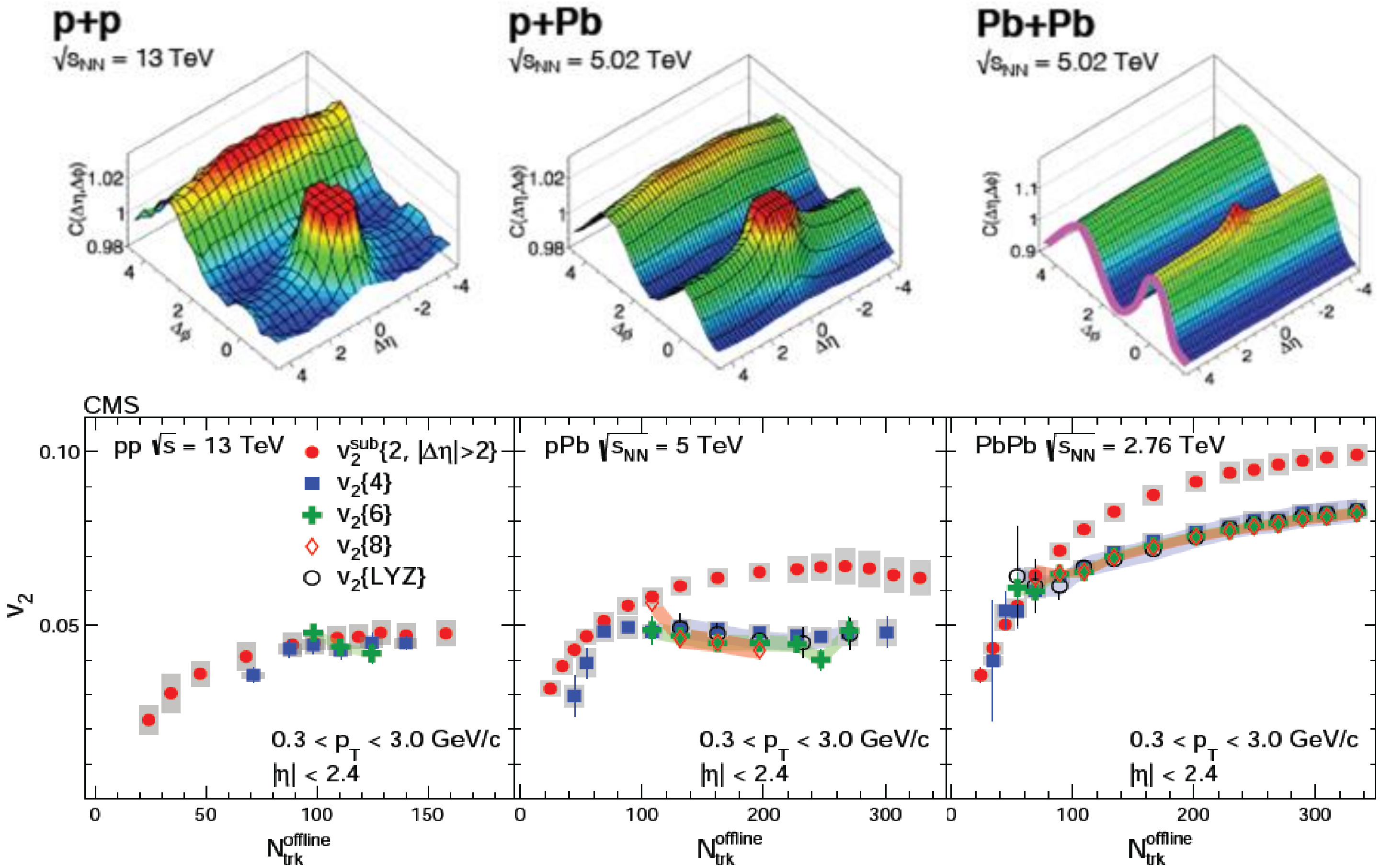
We use jet-particle correlations to study baryon and meson production around jets. We find a strong enhancement of B/M ratios for associated particles at intermediate p_T around the quenched jets, due to the coalescence of jet-excited medium partons.

Luo, Mao, GYQ, Wang, Zhang, 2109.14314

Small systems

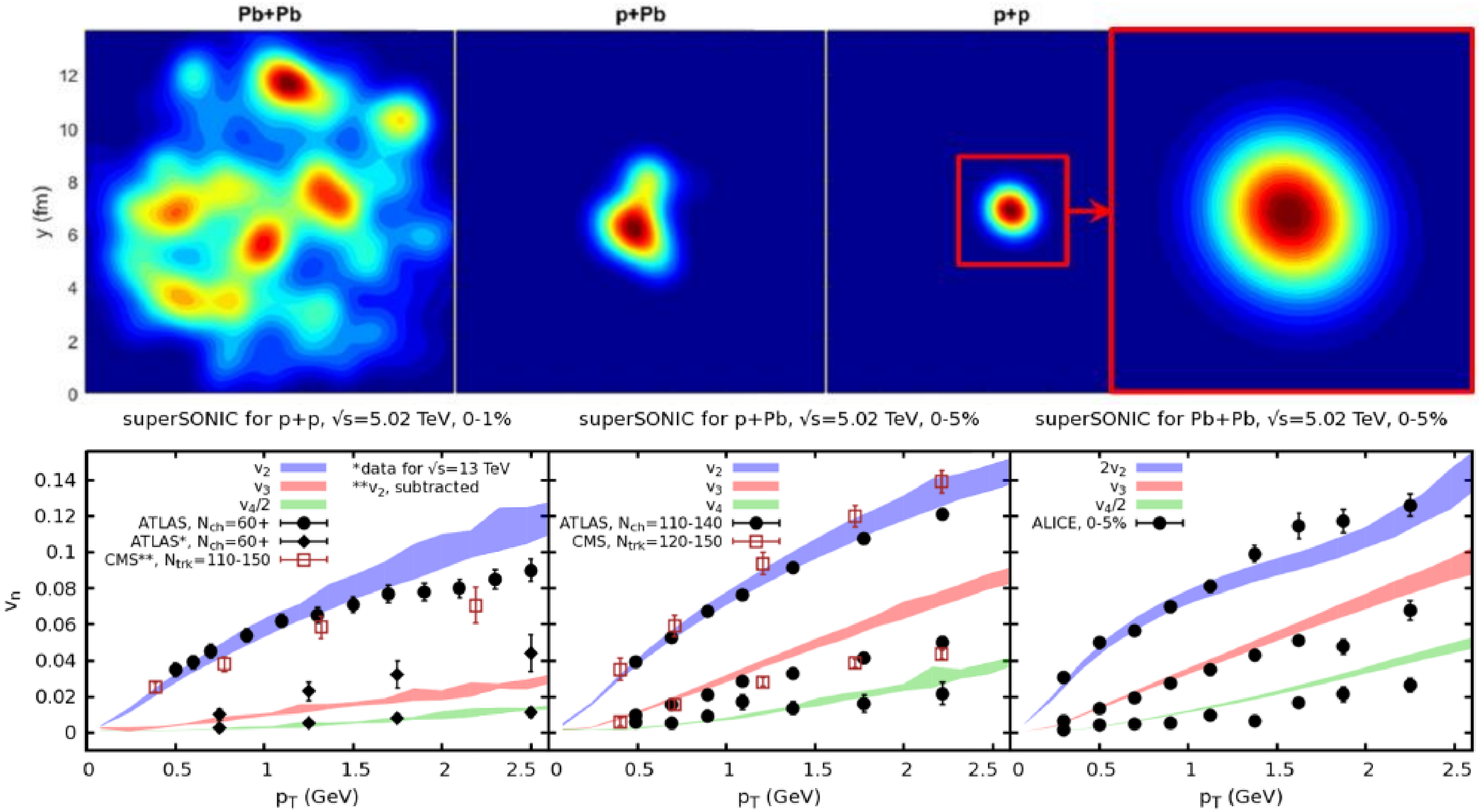
Flow in small collision systems

- **Plenty of evidences for strong collectivity in small collision systems**



What is the dynamical origin of the observed collectivity in small systems?

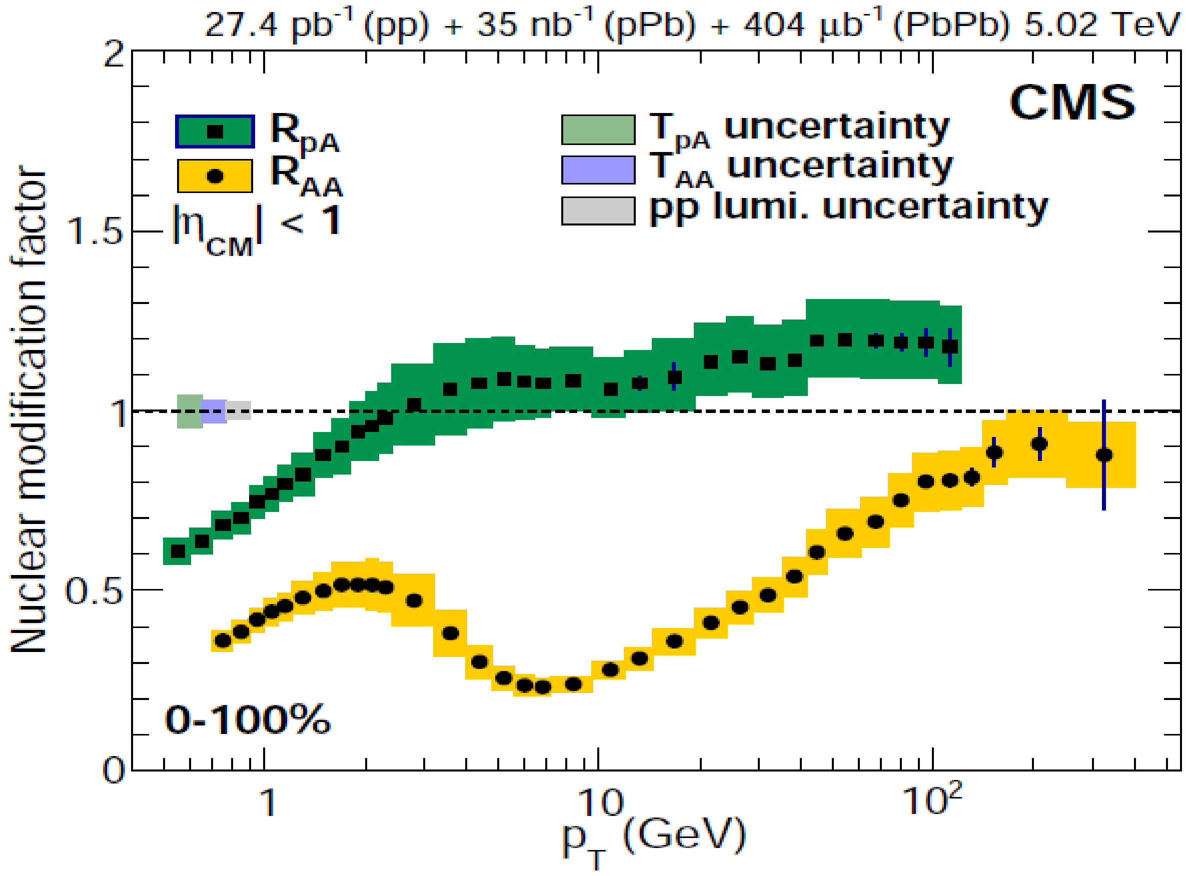
Formation of mini-QGP?



- **The flow harmonics can be viewed as the final-state effect due to hydrodynamic evolution of small collisional systems with certain amount of initial anisotropy.**

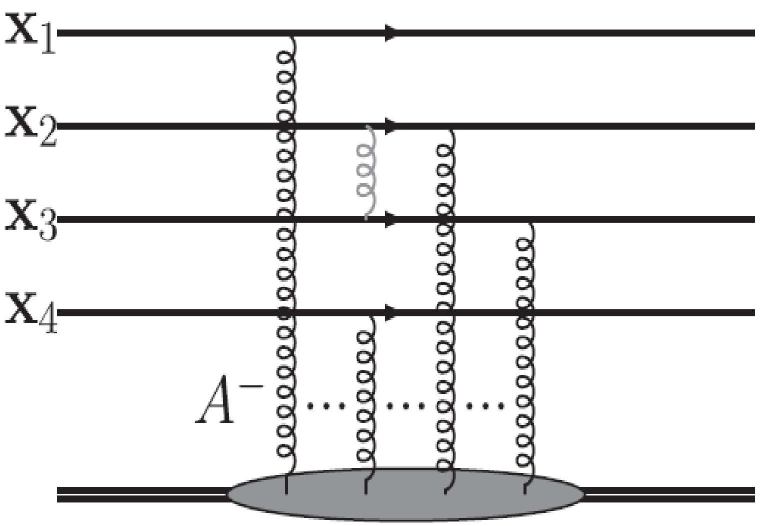
Bozek, Broniowski, Torrieri, PRL 2013; Bzdak, Schenke, Tribedy, Venugopalan, PRC 2013; GYQ, Muller, PRC 2014; Bzdak, Ma, PRL 2014; Weller, Romatschke, PLB 2017; Zhao, Zhou, Xu, Deng, Song, PLB 2018; etc.

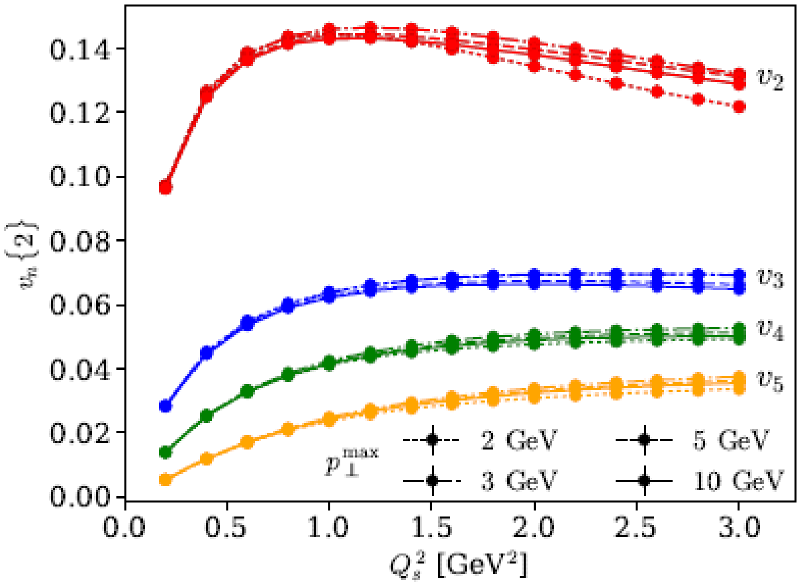
Signature in hard probes?



- Up to now, there is no jet quenching observed in pA collisions

Or initial state effect?

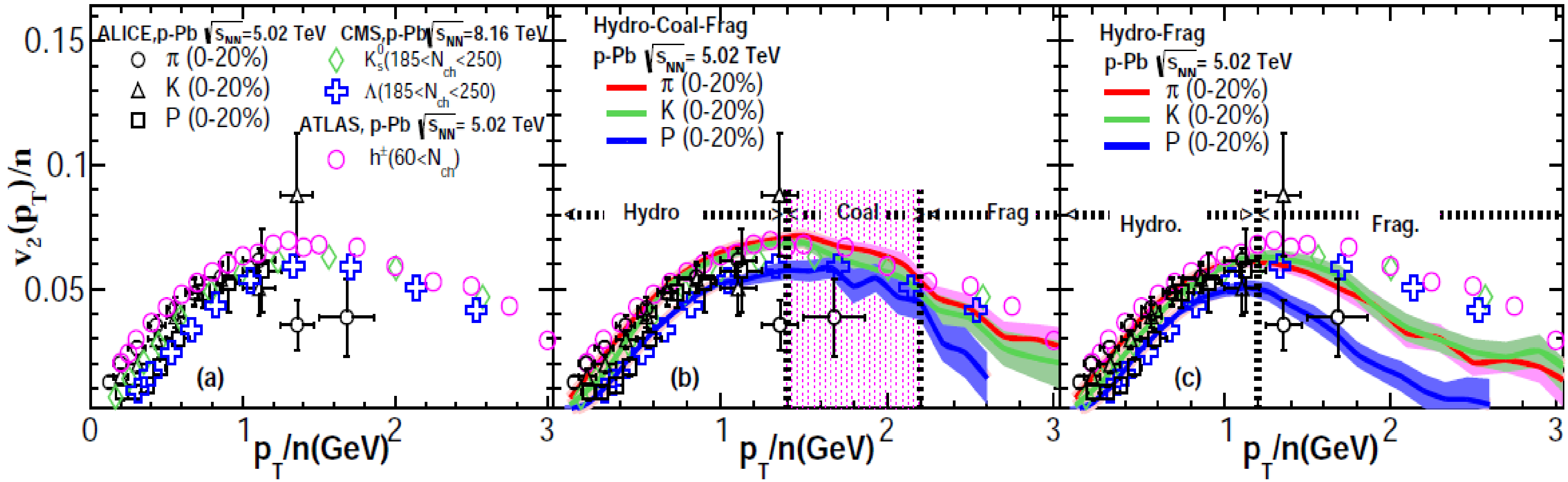




- **In color glass condensate (CGC) dilute-dense factorization framework or the saturation formalism, interactions between partons originated from the projectile proton and dense gluons inside the target nucleus can provide significant amount of collectivity (correlations) among partons.**

Dusling, Mace, Venugopalan, PRL (2018), 1705.00745; PRD (2018), 1706.06260; etc.

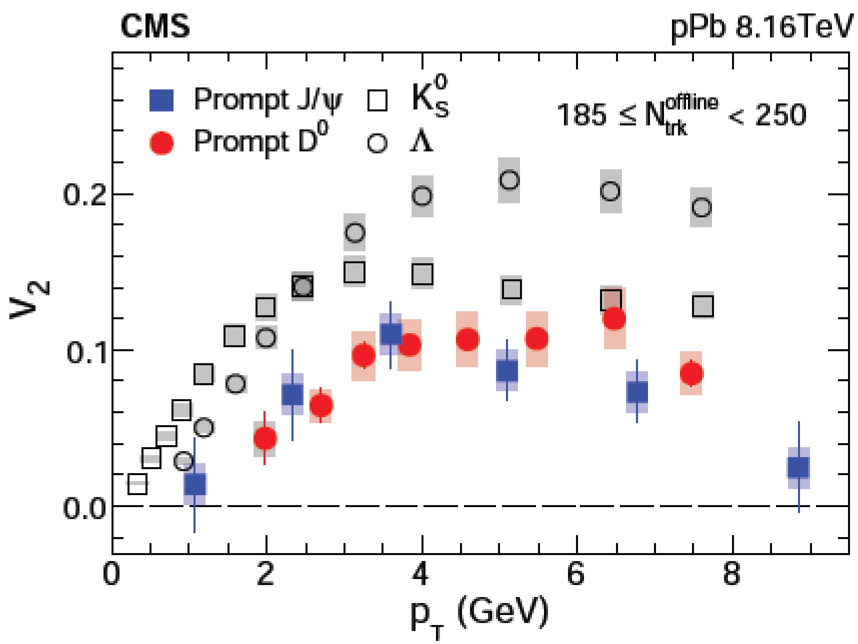
Signature of partonic DOFs in small systems

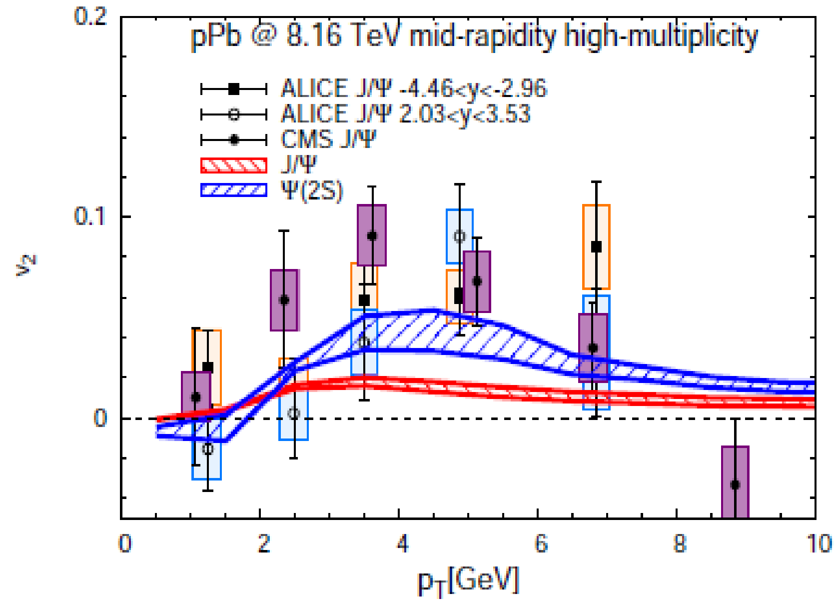


- By combining hydrodynamic simulation and jet quenching, we develop the hybrid hydro+coalescence+fragmentation hadronization mdodel
- To reproduce the observed approximated number of constituent quark (NCQ) scaling of hadron v_2, it is necessary to include the contribution from the constituent quark coalescence at intermediate pT (below 6GeV).
- This result shows the importance of partonic degrees of freedom and supports the formation of mini QGP in high multiplicity p-Pb collisions at the LHC.

Zhao, Ko, Liu, GYQ, Song, PRL 2020

Flow of heavy hadrons in small systems

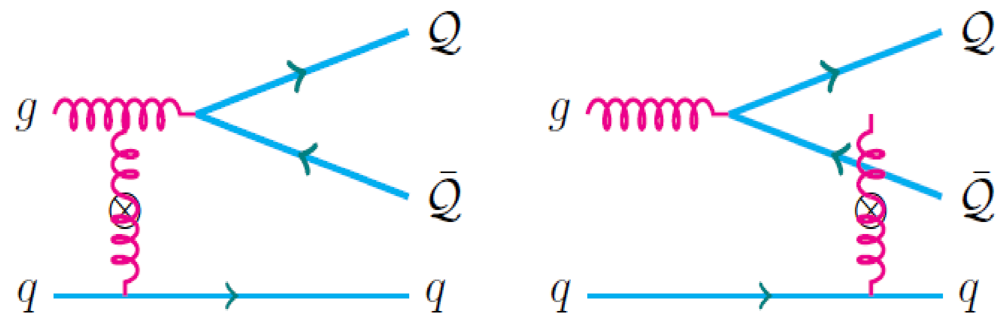




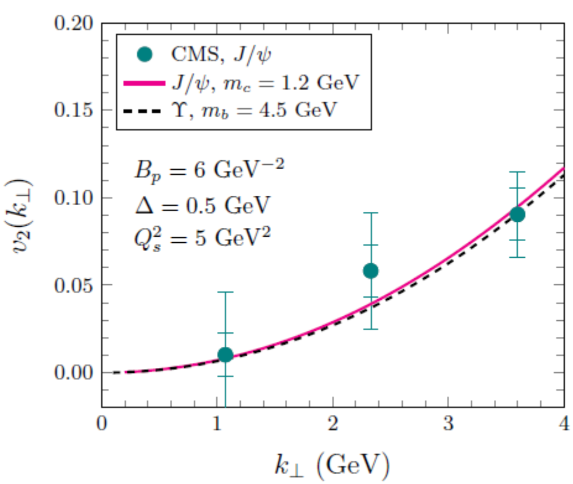
- Large values of elliptic flow v_2 for J/ψ mesons and for D^0 mesons in pPb collisions at the LHC, although they are slightly less than the v_2 values of light hadrons
- Heavy quarks in general do not flow as much as light quarks or gluons due to large masses.
- The final state interactions can only provide a small fraction of the observed v_2 for J/Ψ mesons **[Du, Rapp, JHEP 1903 (2019) 015]**

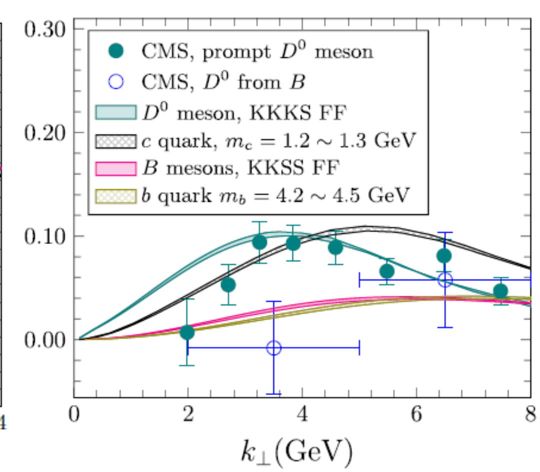
J/Ψ v_2 from initial state correlations

- J/Ψ production together with a reference light quark (which fragments into light hadrons)
- Based on the dilute-dense factorization in color glass condensate (CGC) and the color evaporation model (CEM)
- J/Ψ v_2 can be generated from the interaction between partons from the proton projectile and dense gluons in the nuclear target
- v_2 for other heavy mesons



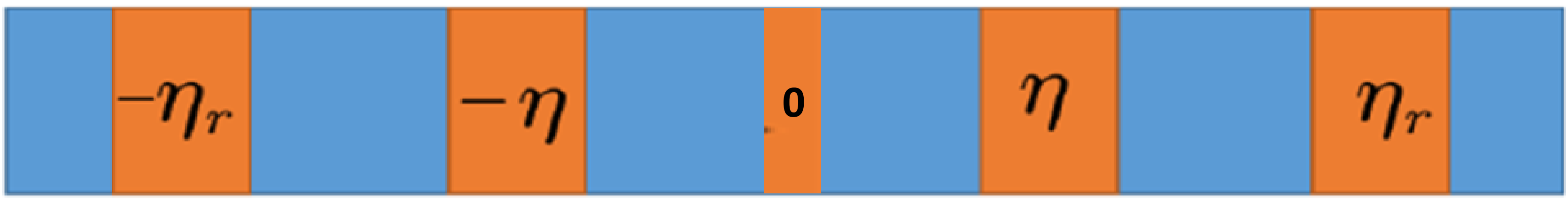
$$v_2[J/\Psi] = V_{2\Delta}[J/\Psi, \mathrm{ref}] \,/\, v_2[\mathrm{ref}]$$





Zhang, Marquet, GYQ, Wei, Xiao, PRL 2019; Zhang, Marquet, GYQ, Wei, Shi, Wang, Xiao, PRD 2020

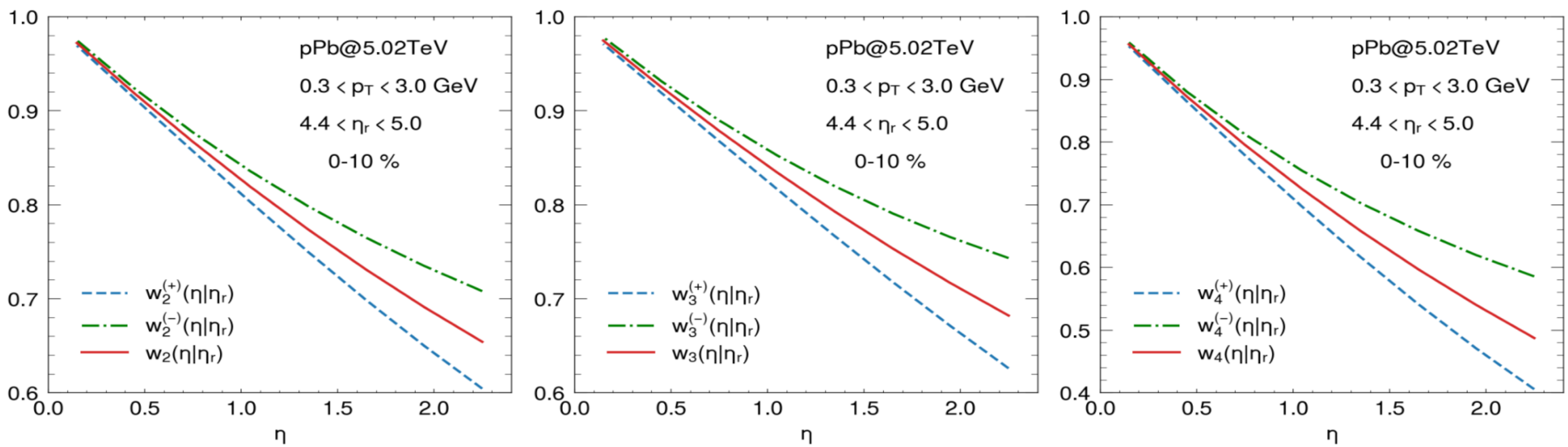
Asymmetric longitudinal flow decorrelations in pA collisions



$$w_n^{(+)}(\eta|\eta_{\rm r}) = \frac{\langle \mathbf{Q}_n(\eta)\mathbf{Q}_n^*(-\eta_{\rm r})\rangle}{\langle \mathbf{Q}_n(0)\mathbf{Q}_n^*(-\eta_{\rm r})\rangle}\frac{\langle \mathbf{Q}_n(0)\mathbf{Q}_n^*(\eta_{\rm r})\rangle}{\langle \mathbf{Q}_n(\eta)\mathbf{Q}_n^*(\eta_{\rm r})\rangle} \qquad w_n^{(-)}(\eta|\eta_{\rm r}) = \frac{\langle \mathbf{Q}_n(-\eta)\mathbf{Q}_n^*(\eta_{\rm r})\rangle}{\langle \mathbf{Q}_n(0)\mathbf{Q}_n^*(\eta_{\rm r})\rangle}\frac{\langle \mathbf{Q}_n(0)\mathbf{Q}_n^*(-\eta_{\rm r})\rangle}{\langle \mathbf{Q}_n(-\eta)\mathbf{Q}_n^*(-\eta_{\rm r})\rangle}$$

$$w_n(\eta|\eta_{\rm r}) = \sqrt{w_n^{(+)}(\eta|\eta_{\rm r})w_n^{(-)}(\eta|\eta_{\rm r})}$$

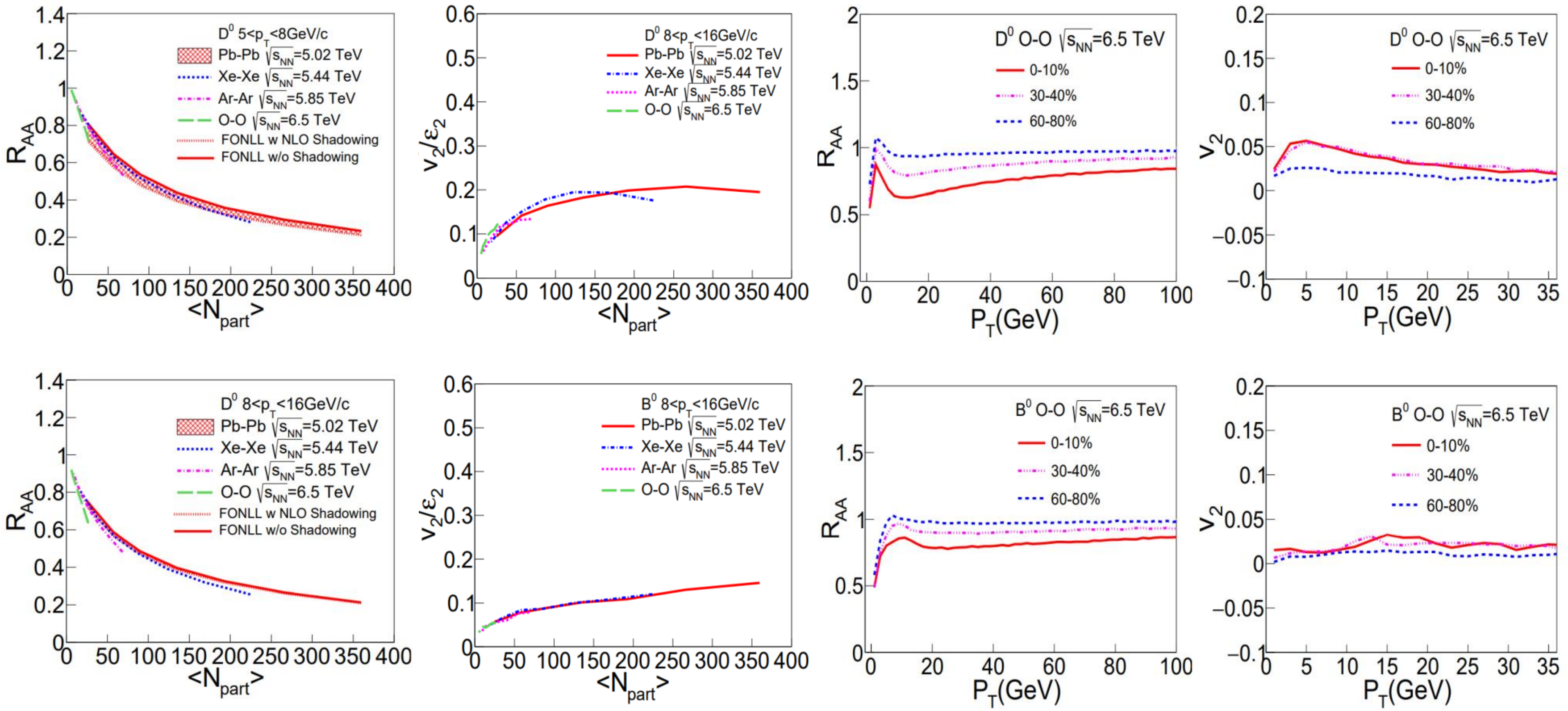
For symmetric systems: $w_n(\eta|\eta_r) = r_n(\eta|\eta_r)$



Flow decorrelations in proton directions are larger than those in nucleus directions.

Wu, GYQ, 2109.03512

Quenching and flow in different systems



D/B meson R_{AA} and v_2 have good scaling behaviors with respect to the systems size。

Our study indicates R_{pA} ~ 1 in pA is mainly due to small system size, and predicts sizable jet quenching in OO collisions.

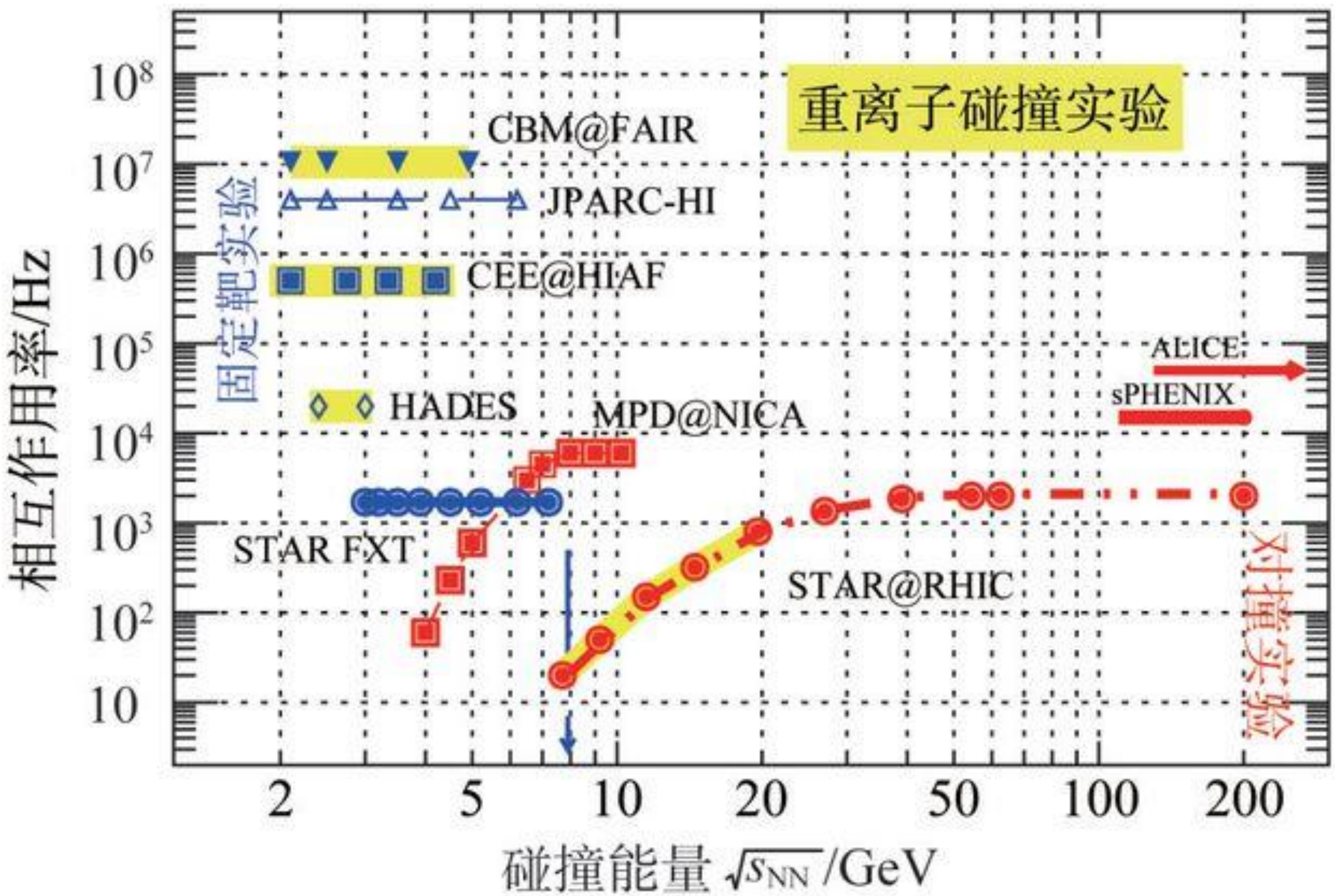
Li, Xing, Wu, Cao, GYQ, EPJC 2021; Liu, Xing, Wu, GYQ, Cao, 2107.01522

Summary

- **Soft probes**
  - Spectra, flow, fluctuations, correlations, decorrelations, etc. for different collision energies and systems
  - Explore the dynamical evolution and collective properties of the QGP at higher precision
- **Hard probes**
  - Heavy & light flavor jet observables: R_{AA}, v_2, full jet, jet-particle correlation, etc.
  - Characterize macroscopic properties and microscopic structures of QCD matter
- **Small systems**
  - Jets and flow
  - Understand the dynamical origins of the collectivity in small and large systems
  - Search for the smallest QGP and the disappearance of QGP

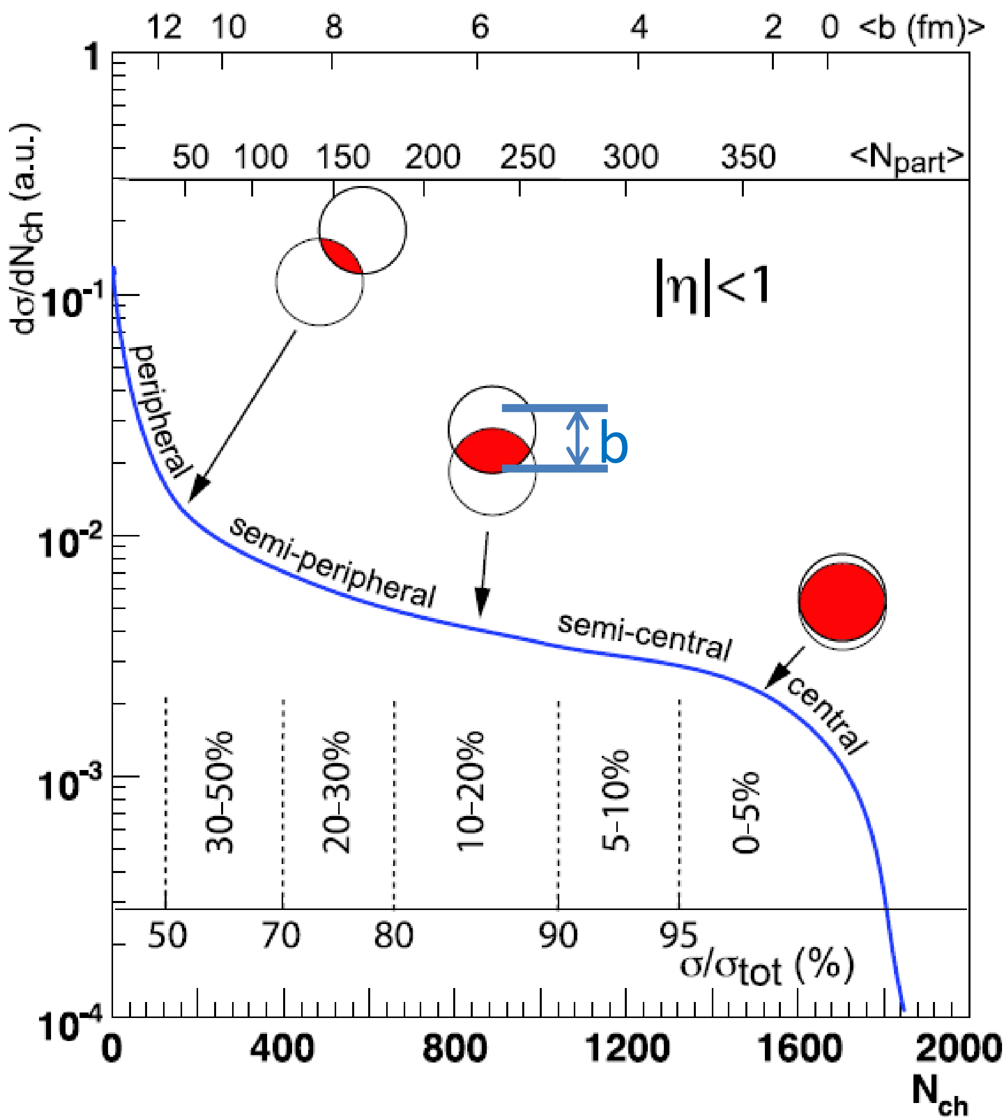
Thank you!

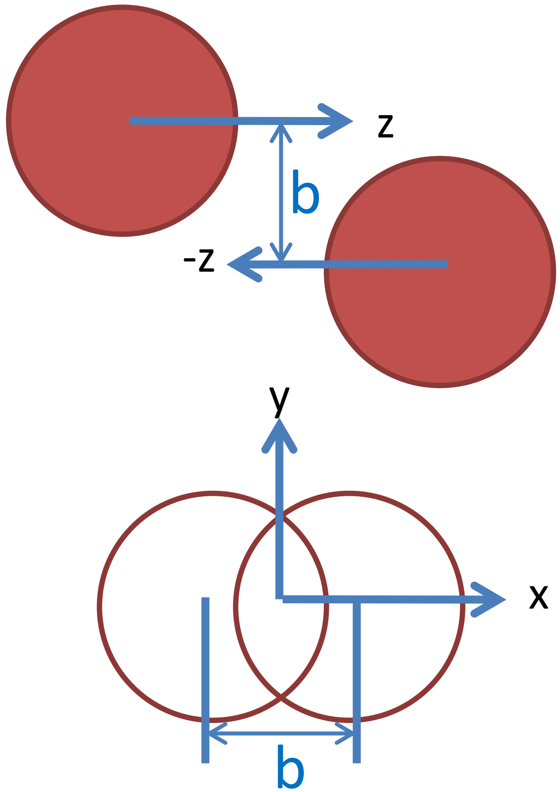
相对论重离子碰撞实验



重离子碰撞实验
CBM@FAIR
JPARC-HI
CEE@HIAF
HADES
MPD@NICA
STAR FXT
STAR@RHIC
ALICE
sPHENIX
固定靶实验
对撞实验
相互作用率/Hz
碰撞能量 $\sqrt{s_{NN}}$/GeV
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
2
5
10
20
50
100
200

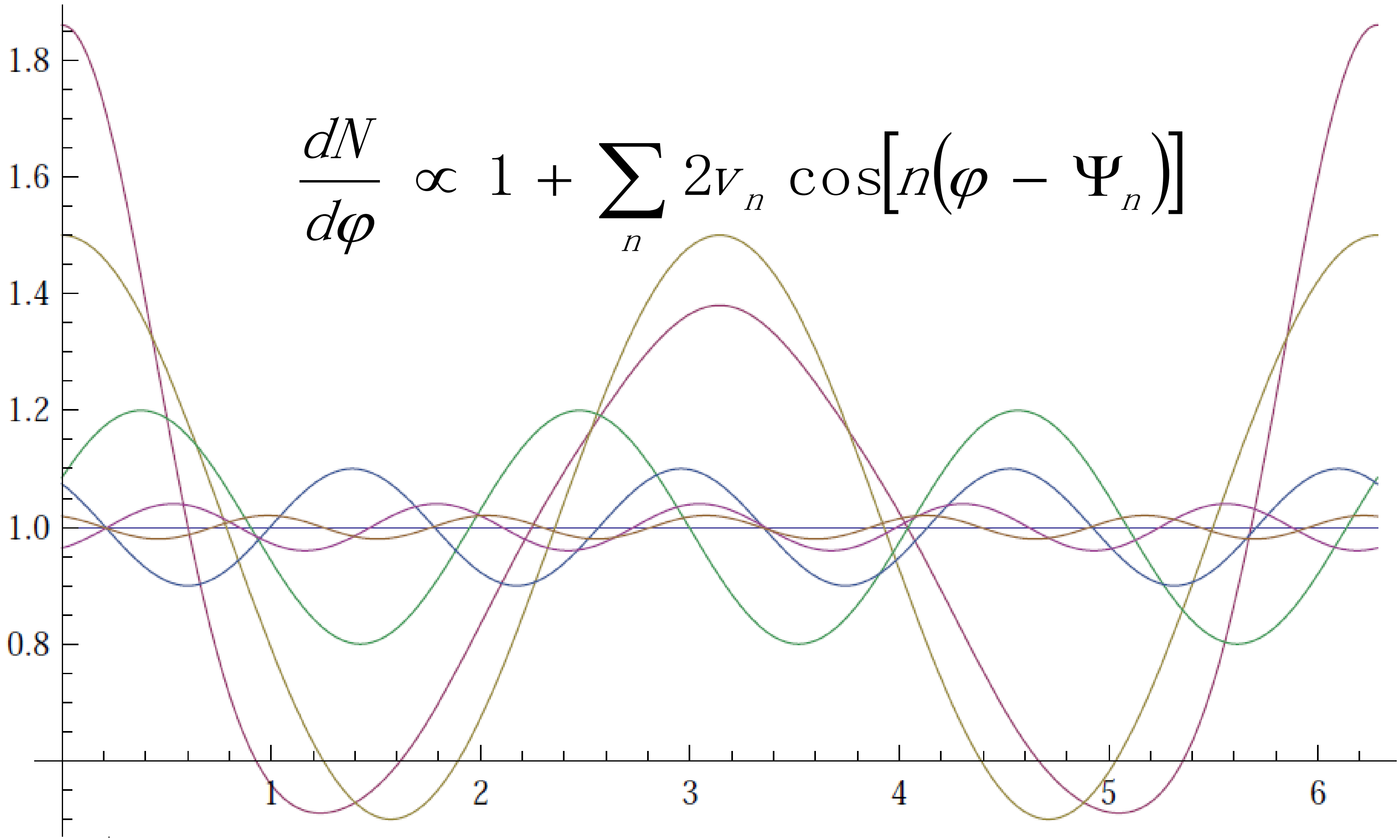
Collision centrality





Miller, Reygers, Sanders, Steinberg, Ann. Rev. Nucl. Part. Sci. 57 (2007) 205-243

Anisotropy: Fourier decomposition



$$\frac{dN}{d\varphi} \propto 1 + \sum_n 2v_n \cos\left[n\left(\varphi - \Psi_n\right)\right]$$

Shear viscosity

- In $\Delta t = \lambda/\bar{v}$, there are on average $\frac{1}{6}n\lambda A_y$ particles from both $y+\lambda$ and $y-\lambda$ passing through the plane at y from above and below.
- The net momentum passing through the plane:

$$\Delta p_x = \frac{1}{6}n\lambda A_y m[u_x(y+\lambda) - u_x(y-\lambda)] = \frac{1}{3}n\lambda^2 A_y m\frac{du_x}{dy}$$

- The drag force:

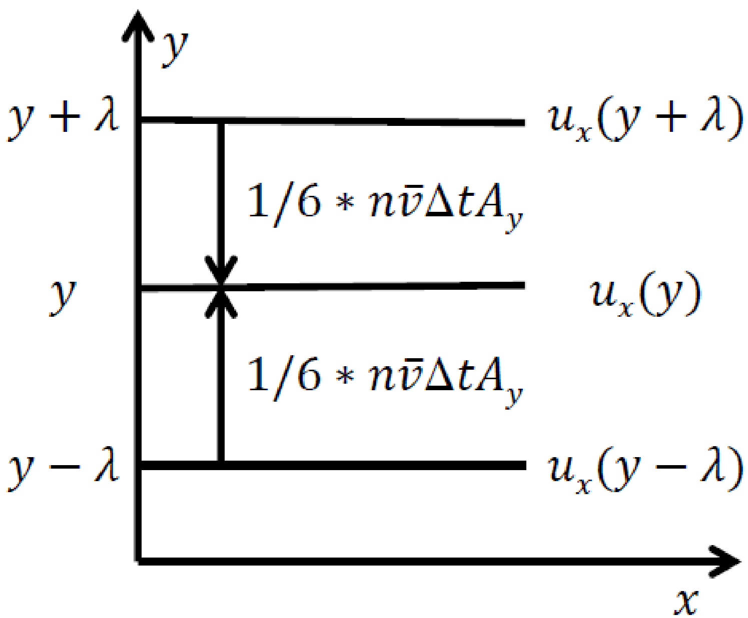
$$F_x = \frac{\Delta p_x}{\Delta t} = \frac{1}{3}n\lambda A_y m\bar{v}\frac{du_x}{dy}$$

- The shear tensor:

$$\frac{F_x}{A_y} = \frac{1}{3}n\lambda m\bar{v}\frac{du_x}{dy} = \eta\frac{du_x}{dy}$$

- The shear viscosity:

$$\eta = \frac{1}{3}n\lambda m\bar{v} = \frac{1}{3}n\lambda\bar{p}$$



Relativistic hydrodynamics

- Energy-momentum conservation:

$$\partial_\mu T^{\mu\nu} = 0$$

$$T^{\mu\nu} = \varepsilon U^\mu U^\nu - (P + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

- Equations of motion (Israel-Stewart viscous hydrodynamics):

$$\dot{\varepsilon} = -(\varepsilon + P + \Pi)\theta + \pi^{\mu\nu}\sigma_{\mu\nu}$$

$$(\varepsilon + P + \Pi)\dot{U}^\alpha = \nabla^\alpha(P + \Pi) + \dot{U}_\mu \pi^{\mu\nu} - \Delta^\alpha_\nu \nabla_\mu \pi^{\mu\nu}$$

$$\dot{\Pi} = -\frac{1}{\tau_\Pi}\left[\Pi + \zeta\theta + \Pi\zeta T \partial_\alpha\left(\frac{\tau_\Pi}{2\zeta T}U^\alpha\right)\right]$$

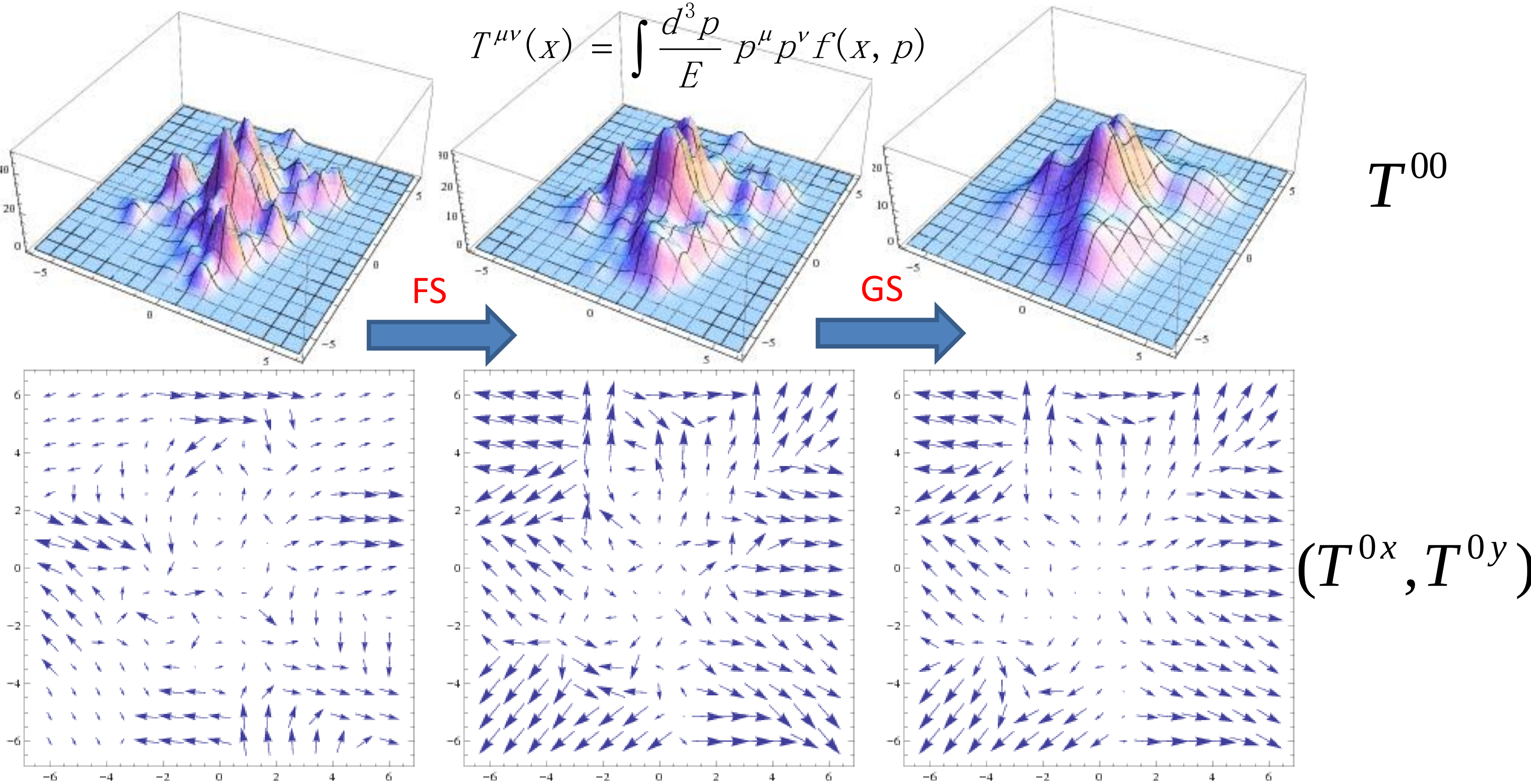
$$\Delta^{\mu\nu}_{\alpha\beta}\dot{\pi}^{\alpha\beta} = -\frac{1}{\tau_\pi}\left[\pi^{\mu\nu} - 2\eta\sigma^{\mu\nu} + \pi^{\mu\nu}\eta T \partial_\alpha\left(\frac{\tau_\pi}{2\eta T}U^\alpha\right)\right]$$

- Equation of state: $P = P(\varepsilon)$

arXiv:0902.3663; arXiv:1301.2826; arXiv:1301.5893; arXiv:1311.1849; arXiv:1401.0079…

Initial conditions before hydro

$$T^{\mu\nu}(x) = \int \frac{d^3p}{E} p^\mu p^\nu f(x, p)$$



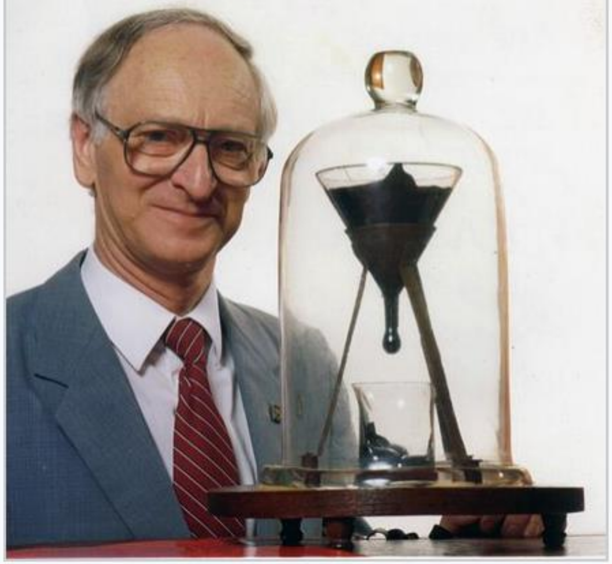
t_0=0, σ_{xy}=0.3fm | **t_0=0.6fm/c, σ_{xy}=0.3fm** | **t_0=0.6fm/c, σ_{xy}=0.5fm** | **b=8fm**

GYQ, Petersen, Bass, Muller, PRC, 2010

Pitch Drop Experiment

Time	Event	Duration (Year)
1927	Hot pitch poured	
1930.10	Stem cut	
1938.12	1st drop fell	8.1
1947.2	2nd drop fell	8.2
1954.4	3rd drop fell	7.2
1962.5	4th drop fell	8.1
1970.8	5th drop fell	8.3
1979.4	6th drop fell	8.7
1988.7	7th drop fell	9.2
2000.11	8th drop fell	12.3
2014.4	9th drop fell	13.4

2005 Ig Nobel Prize



The University of Queensland pitch drop experiment, featuring its then-current custodian, Professor John Mainstone (taken in 1990, two years after the seventh drop and 10 years before the eighth drop fell).

Edgeworth, Dalton, Parnell, Eur. J. Phys. (1984) 198.

Guinness World Record
for the longest-running laboratory experiment

Most perfect fluid

Brookhaven National Laboratory Newsroom Media & Communications Office

Newsroom Photos Videos Fact Sheets Lab History News Categories

Contact: Karen McNulty Walsh, (631) 344-8350, or Peter Genzer, (631) 344-3174

share:

RHIC Scientists Serve Up 'Perfect' Liquid

New state of matter more remarkable than predicted — raising many new questions

April 18, 2005

TAMPA, FL — The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) — a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory — say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

Collectivity!
Strongly-coupled!
Perfect!

Brookhaven National Laboratory Newsroom Media & Communications Office

Newsroom Photos Videos Fact Sheets Lab History News Categories

By Karen McNulty Walsh

share:

RHIC's Perfect Liquid a Study in Perfection

Systematic analysis of particle flow in heavy ion experiments suggests that RHIC's shear viscosity is close to ideal limit

June 17, 2013

Space is supported by its audience. When you purchase through links on our site, we may earn an affiliate

in cooperation with livescience

Home > News > Science & Astronomy

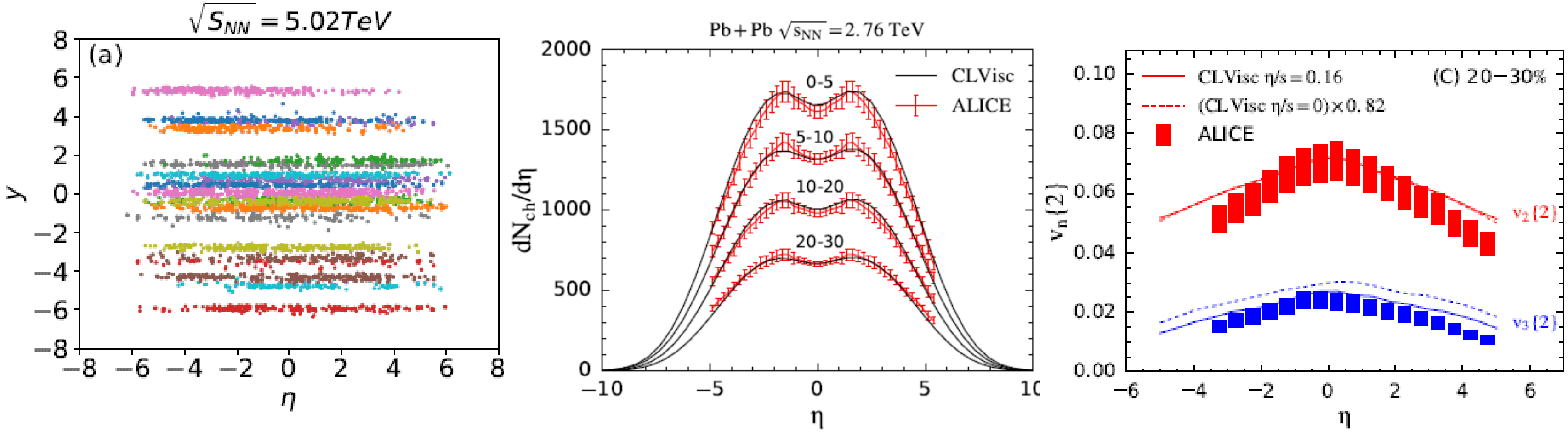
1st matter in the universe may have been a perfect liquid

By Mara Johnson-Groh published June 05, 2021

Scientists have recreated the first matter that appeared after the Big Bang in the Large Hadron Collider.

Longitudinal fluctuations

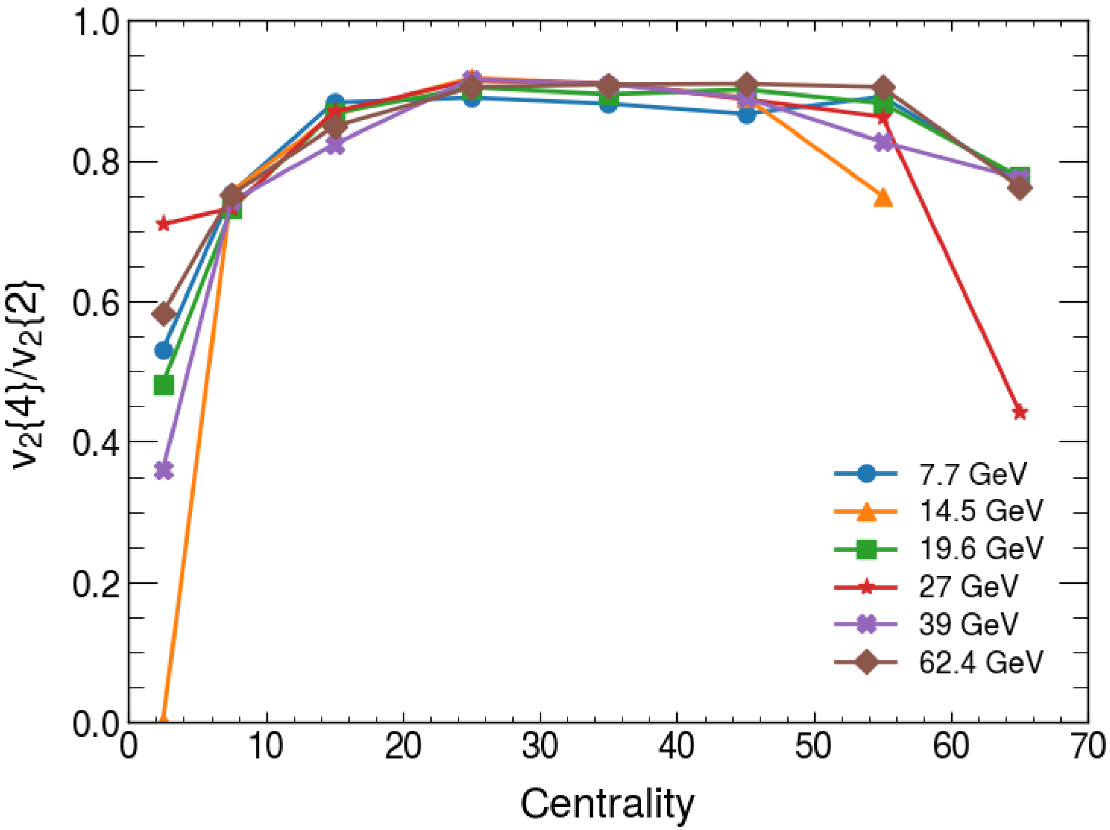
- The initial states are fluctuating also in longitudinal (rapidity) directions



- Longitudinal fluctuations can lead to rapidity-dependent particle yield and v_n
- The rapidity dependence (decorrelation) of v_n provide another tool to probe the QGP properties

Gabriel et al. PRL 2016; Pang, Petersen, Wang PRC 2018; Wu, Pang, GYQ, Wang, PRC 2018

CLvisc (3+1)-D hydrodynamics for BES energies



The relative fluctuations of v_2 are smallest in mid-central collisions, and become larger in central and peripheral collisions.

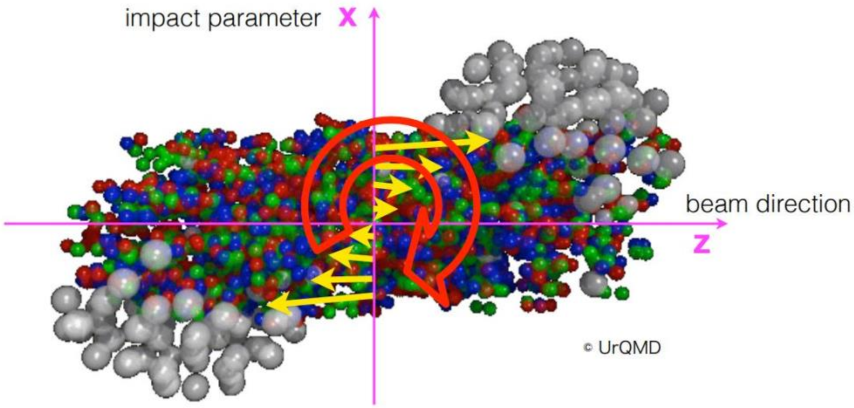
In mid-central collisions, v_2 is more dominated by the elliptic collision geometry.

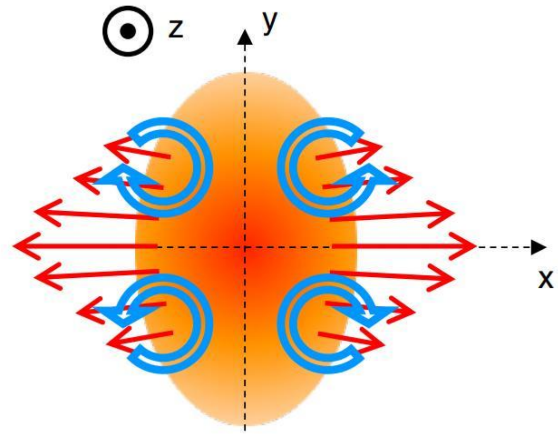
In central and periperal collisions, v_2 is more dominated by initial state fluctuations.

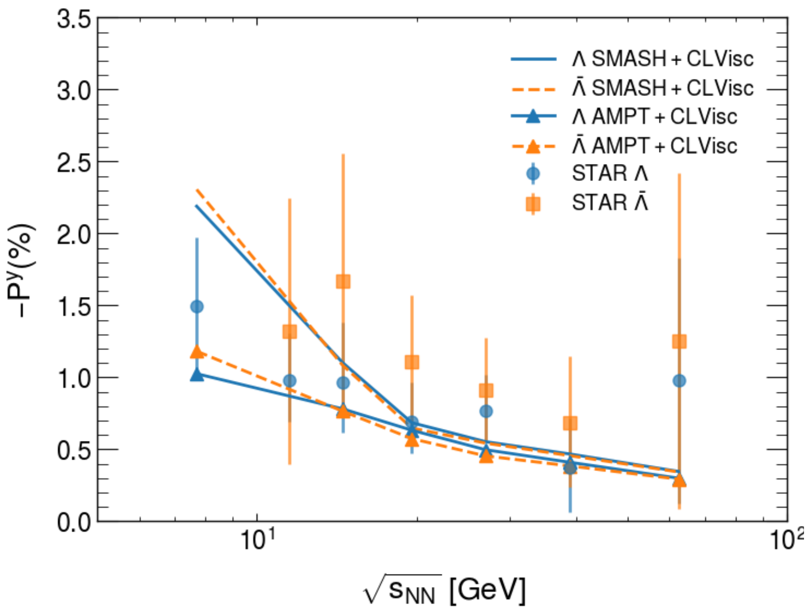
The relative fluctuations of v_2 are insensitive to collision energy (consistent with STAR preliminary data)

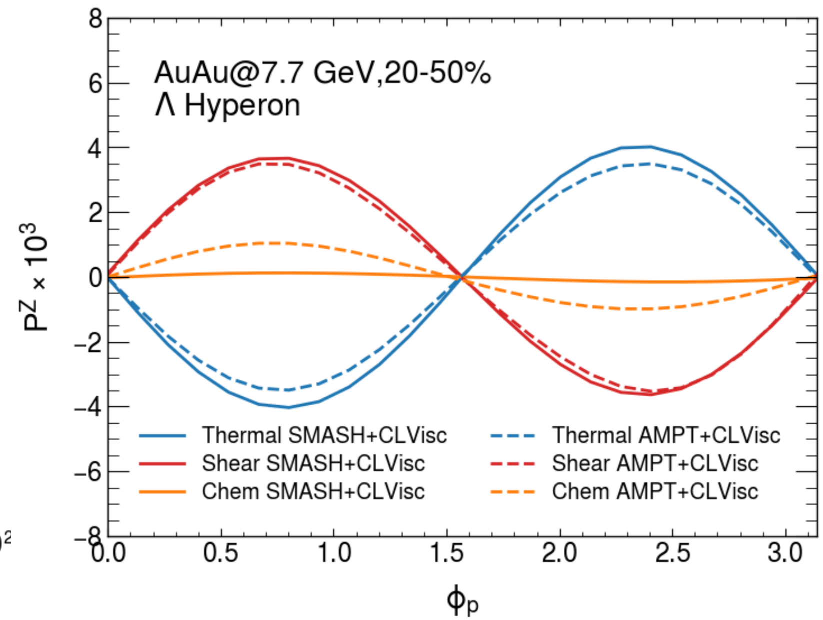
Wu, GYQ, Pang, Wang, 2107.04949

Global and local Λ polarization at BES energies



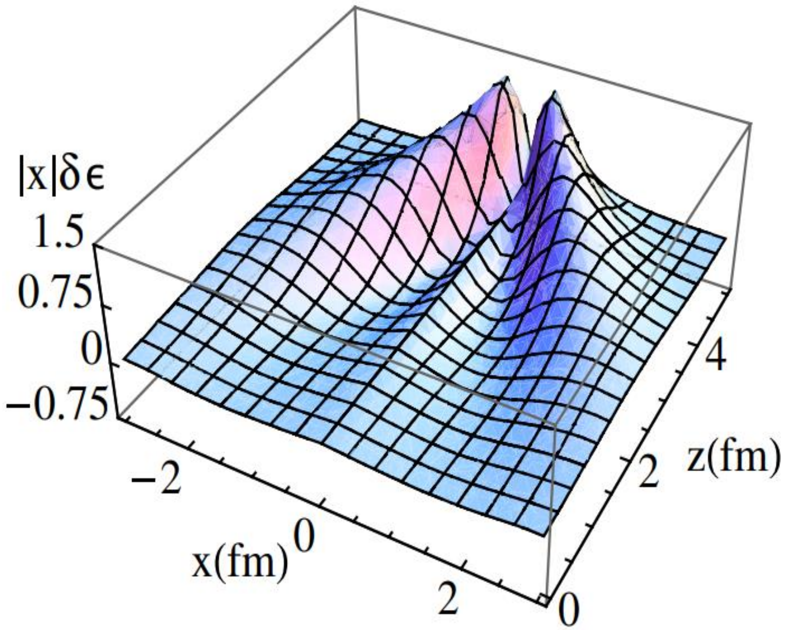


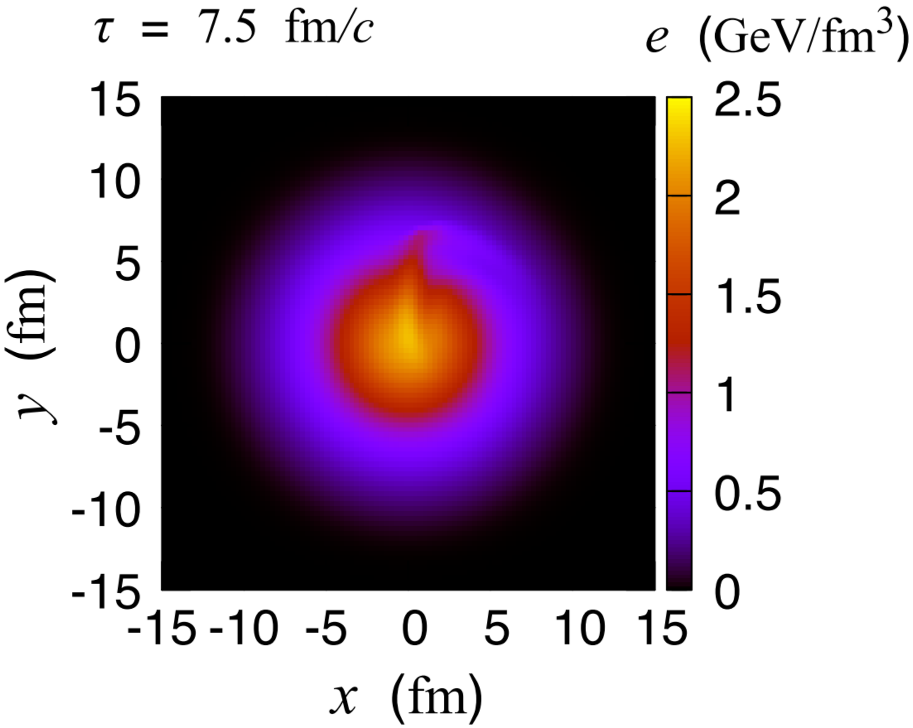




Wu, GYQ et al, in preparation

Medium response



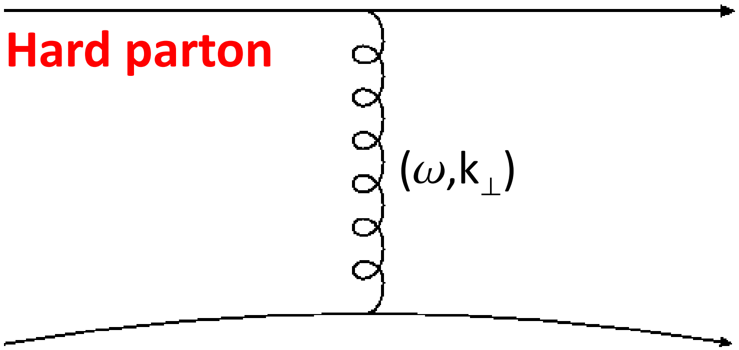


Jets lose energy into medium, which can induce medium excitations.

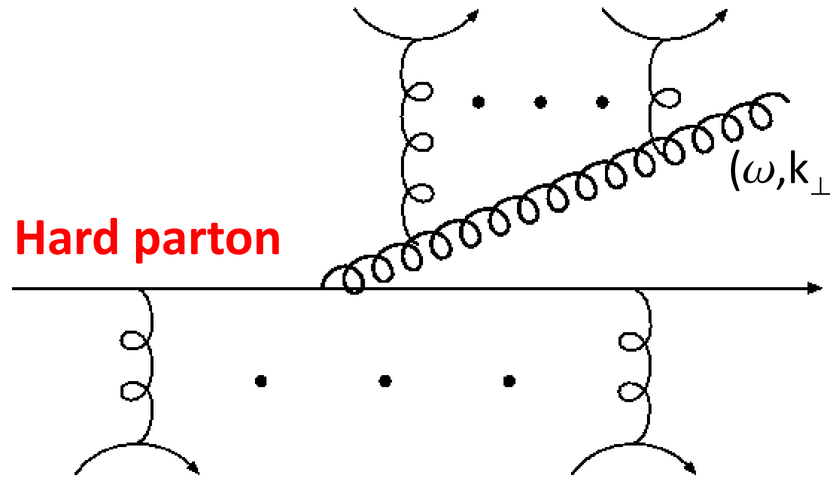
The direct detection of medium response is extremely difficult since the collective flow of the dynamic medium can significantly distort the Mach cone structure.

GYQ, Majuder, Song, Heinz, Phys. Rev. Lett. 103, 152303 (2009)
Tachibana, Chang, GYQ, Phys. Rev. C 95, 044909 (2017)

Elastic and inelastic interactions



Elastic (collisional)



Inelastic (radiative)

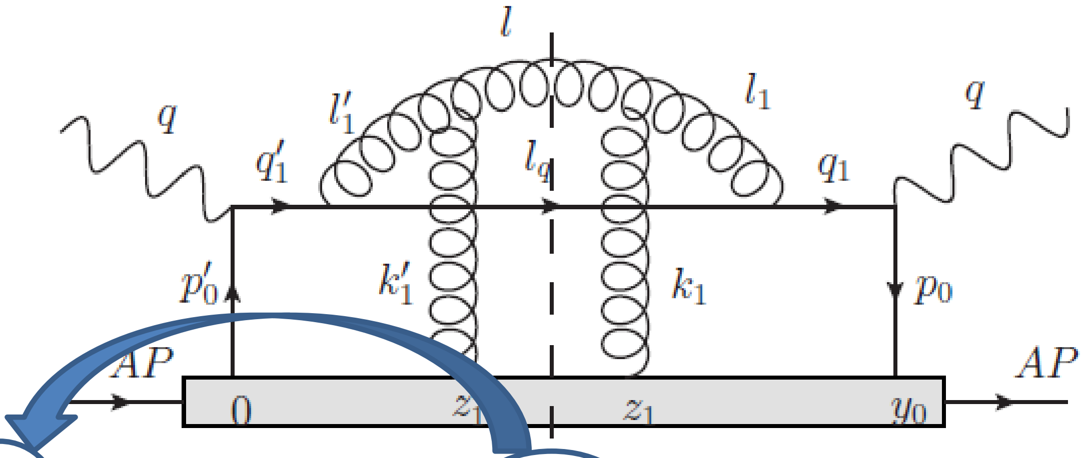
$$\frac{d\Gamma_{coll}}{d\omega dk_\perp^2 dt}(T, E, \ldots) = ?$$

$$\frac{d\Gamma_{rad}}{d\omega dk_\perp^2 dt}(T, E, \ldots) = ?$$

Bjorken 1982; Bratten, Thoma 1991; Thoma, Gyulassy, 1991; Mustafa, Thoma 2005; Peigne, Peshier, 2006; Djordjevic, 2006; Wicks et al (DGLV), 2007; GYQ et al (AMY), 2008; …

BDMPS-Z: Baier-Dokshitzer-Mueller-Peigne-Schiff-Zakharov
ASW: Amesto-Salgado-Wiedemann
AMY: Arnold-Moore-Yaffe (& Caron-Huot, Gale)
GLV: Gyulassy-Levai-Vitev (& Djordjevic, Heinz)
HT: Wang-Guo (& Zhang, Wang, Majumder)

Medium-induced inelastic (radiative) process



Zhang, Hou, GYQ, PRC 2018 & PRC 2019; Zhang, GYQ, Wang, PRD 2019.

+ other 20 diagrams

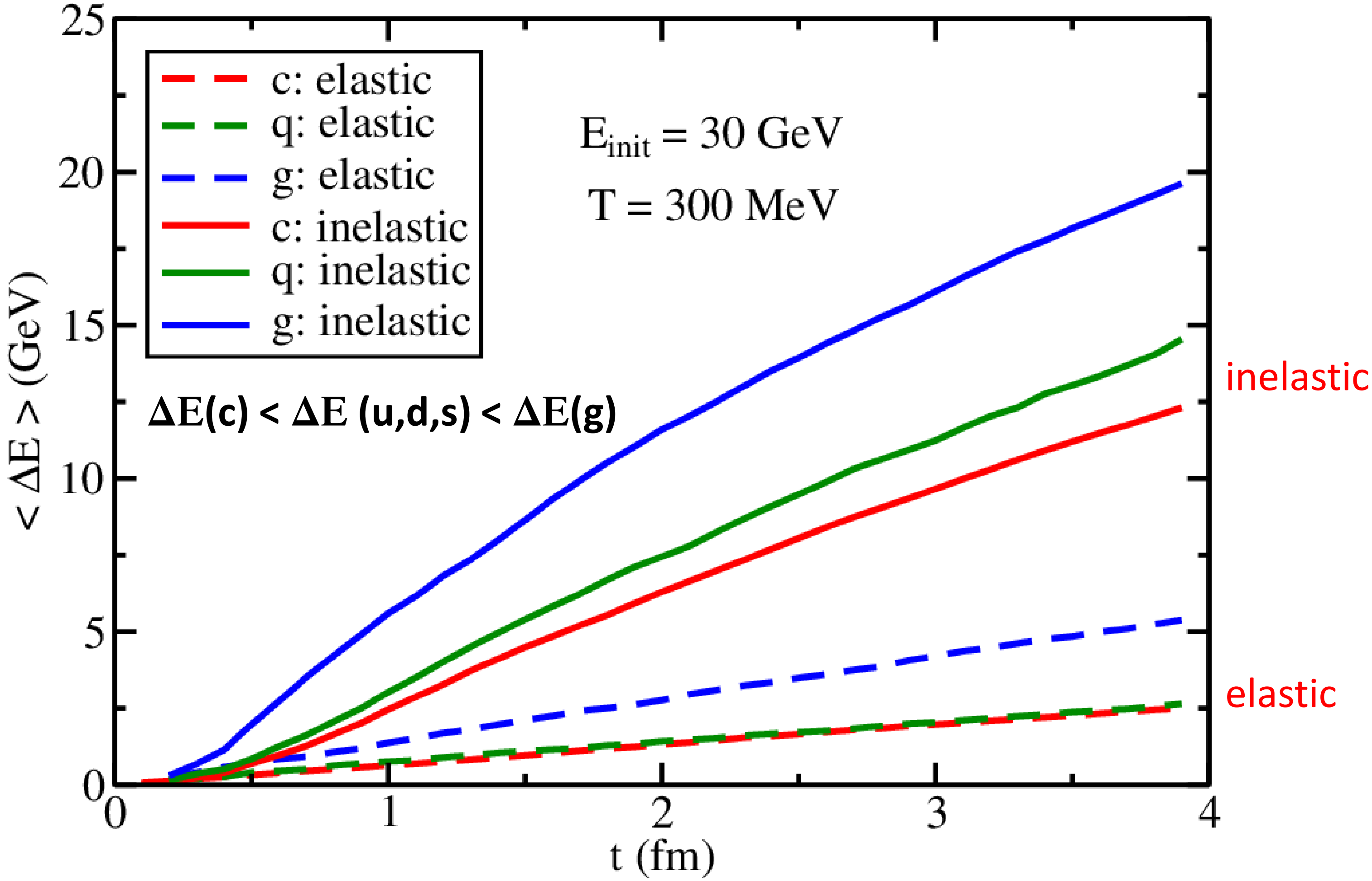
$$\mathcal{D}(k_1^-, \mathbf{k}_{1\perp}) = (2\pi)^3 \frac{dP_{\rm el}}{dk_1^- d^2\mathbf{k}_{1\perp} dZ_1^-}$$

Medium-induced gluon emission spectrum is directly controlled by differential elastic scattering rate

$$\frac{dN_g^{med}}{dy d^2\mathbf{l}_\perp} = \frac{\alpha_s}{2\pi^2} P(y) \int dZ_1^- \int \frac{dk^- d^2\mathbf{k}_{1\perp}}{(2\pi)^3} \mathcal{D}(k_1^-, \mathbf{k}_{1\perp})$$
$$\times \left\{ \left[2 - 2\cos\left(\frac{y(1-y)}{(y-\lambda_1^-)(1+\lambda_1^- - y)} \frac{(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + (y-\lambda_1^-)^2 M^2}{l_\perp^2 + y^2 M^2} \frac{Z_1^-}{\tilde{\tau}_{\rm form}^-} \right) \right] \right.$$
$$C_A \left[\frac{1 + (1+\lambda_1^- - y)^2}{1 + (1-y)^2} \left(\frac{y - \frac{\lambda_1^-}{2}}{y - \lambda_1^-} \right)^2 \frac{(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + \frac{(y-\lambda_1^-)^4 M^2}{1+(1+\lambda_1^- - y)^2}}{[(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + (y-\lambda_1^-)^2 M^2]^2} \right.$$
$$- \frac{1 + (1+\lambda_1^- - y)(1-y)}{2[1+(1-y)^2]} \left(\frac{y - \frac{\lambda_1^-}{2}}{y - \lambda_1^-} \right) \frac{\mathbf{l}_\perp \cdot (\mathbf{l}_\perp - \mathbf{k}_{1\perp}) + \frac{y^2 (y-\lambda_1^-)^2}{1+(1+\lambda_1^- - y)(1-y)} M^2}{[l_\perp^2 + y^2 M^2] \left[(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + (y-\lambda_1^-)^2 M^2 \right]}$$
$$\left. \left. - \frac{1 + (1+\lambda_1^- - y)(1 - \frac{y}{1+\lambda_1^-})}{2[1+(1-y)^2]} \left(\frac{y - \frac{\lambda_1^-}{2}}{y - \lambda_1^-} \right) \frac{(\mathbf{l}_\perp - \mathbf{k}_{1\perp}) \cdot \left(\mathbf{l}_\perp - \frac{y}{1+\lambda_1^-} \mathbf{k}_{1\perp} \right) + \frac{\left(\frac{y}{1+\lambda_1^-} \right)^2 (y-\lambda_1^-)^2}{1+(1+\lambda_1^- - y)(1 - \frac{y}{1+\lambda_1^-})} M^2}{\left[\left(\mathbf{l}_\perp - \frac{y}{1+\lambda_1^-} \mathbf{k}_{1\perp} \right)^2 + (\frac{y}{1+\lambda_1^-})^2 M^2 \right] \left[(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + (y-\lambda_1^-)^2 M^2 \right]} \right] + \ldots\ldots \right\}$$

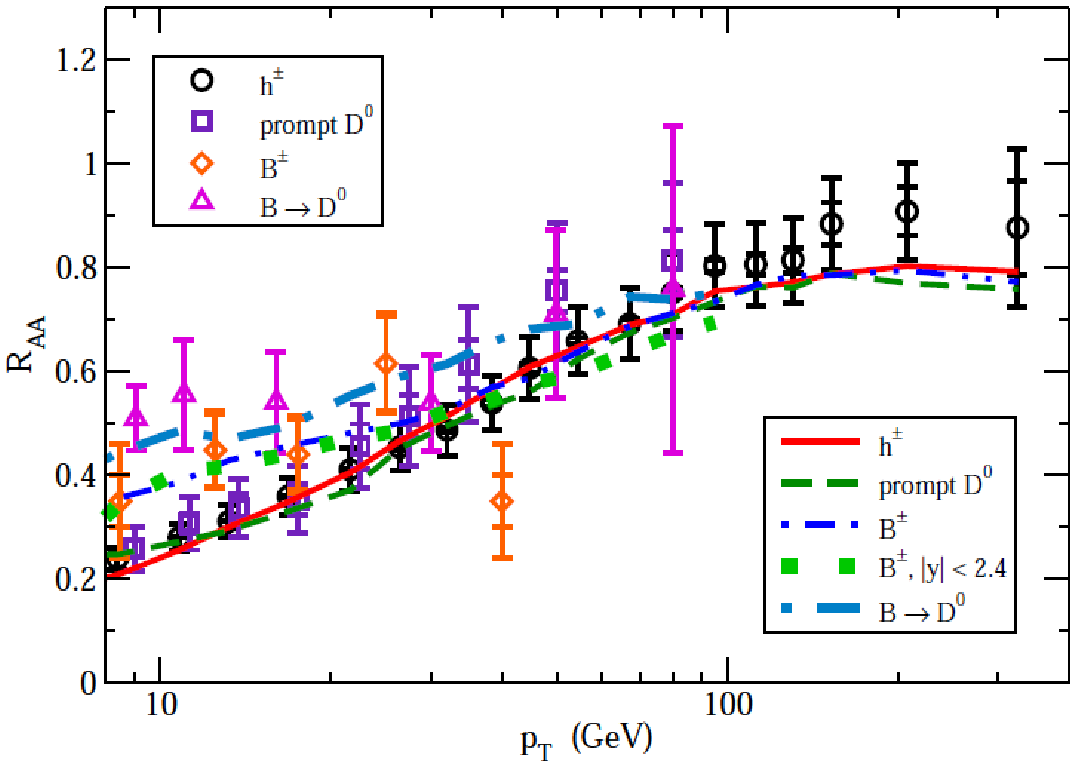
Medium-induced gluon emission beyond collinear expansion & soft emission limit with transverse & longitudinal scatterings for massive/massless quarks

Parton energy loss in LBT



He, Luo, Wang, Zhu, PRC 2015; Cao, Luo, GYQ, Wang, PRC 2016 ; PLB 2018; etc.

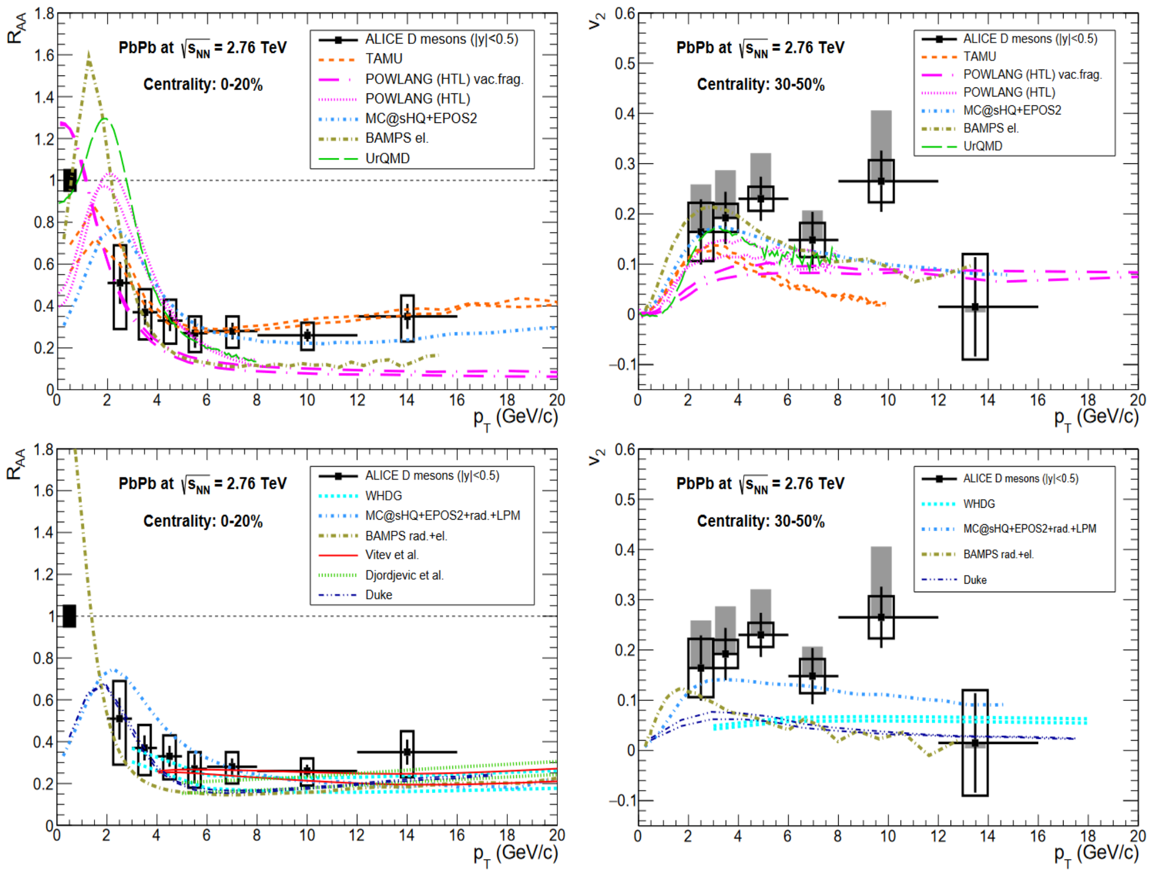
Flavor hierarchy of jet quenching

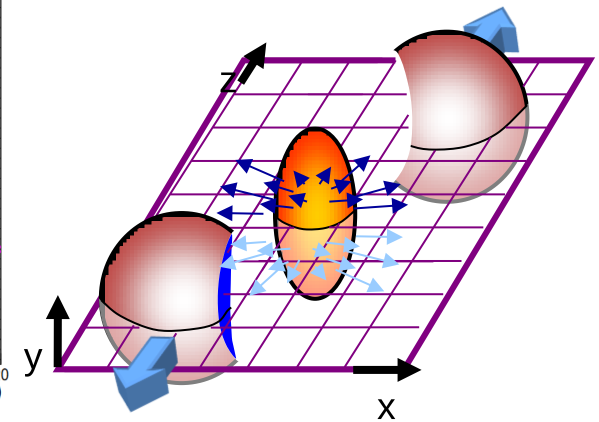


- A state-of-art jet quenching framework (NLO-pQCD + LBT + Hydrodynamics)
- At p_T > 30-40 GeV, B mesons will also exhibit similar suppression effects to charged hadrons and D mesons, which can be tested by future measurements.

Xing, Cao, GYQ, Xing, PLB 2020

Heavy flavor R_{AA} and v_2 puzzle



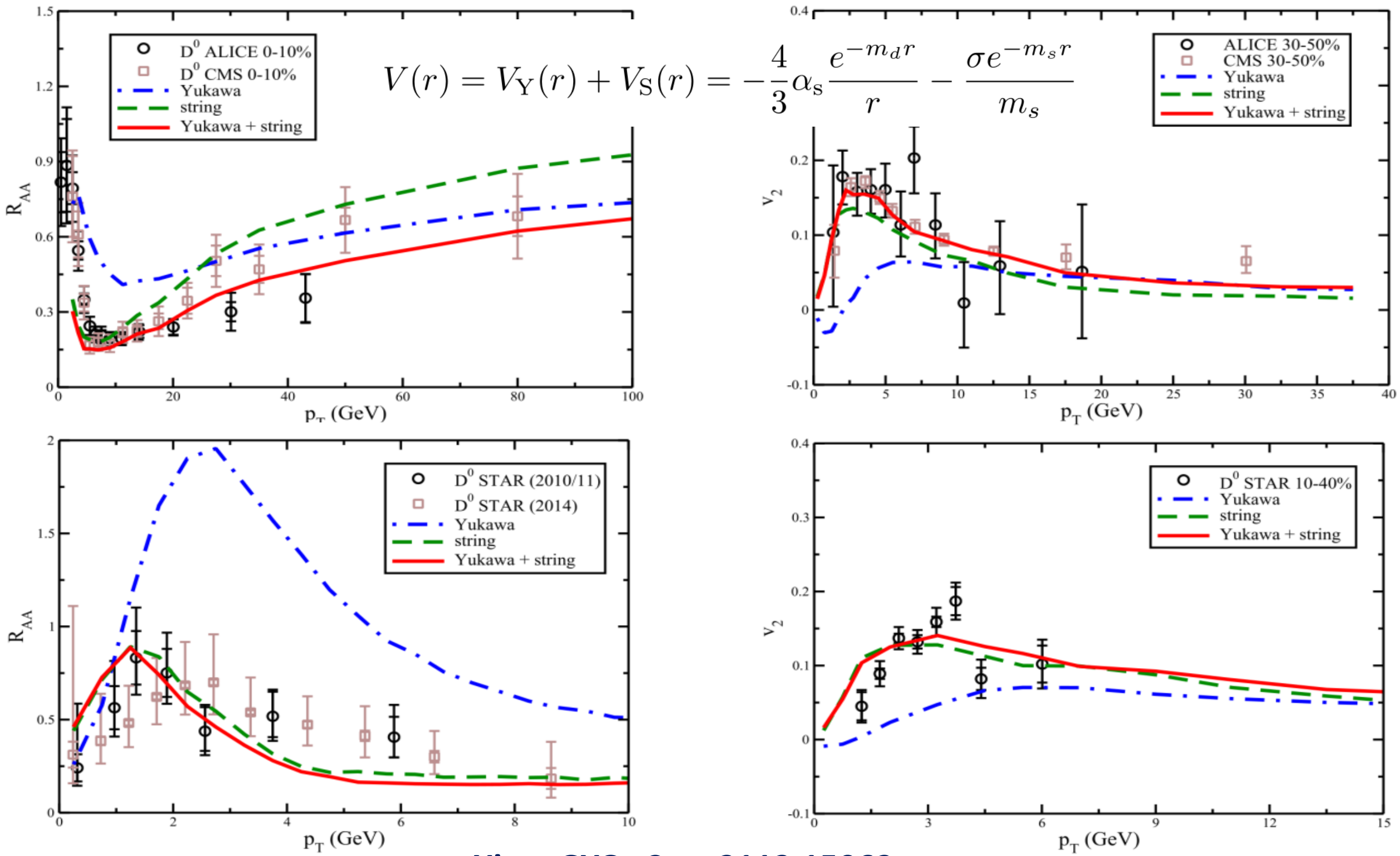


It is difficult for models to simultaneouly describe R_{AA} and v_2 for D mesons

Eur.Phys.J.C 76 (2016) 3, 107

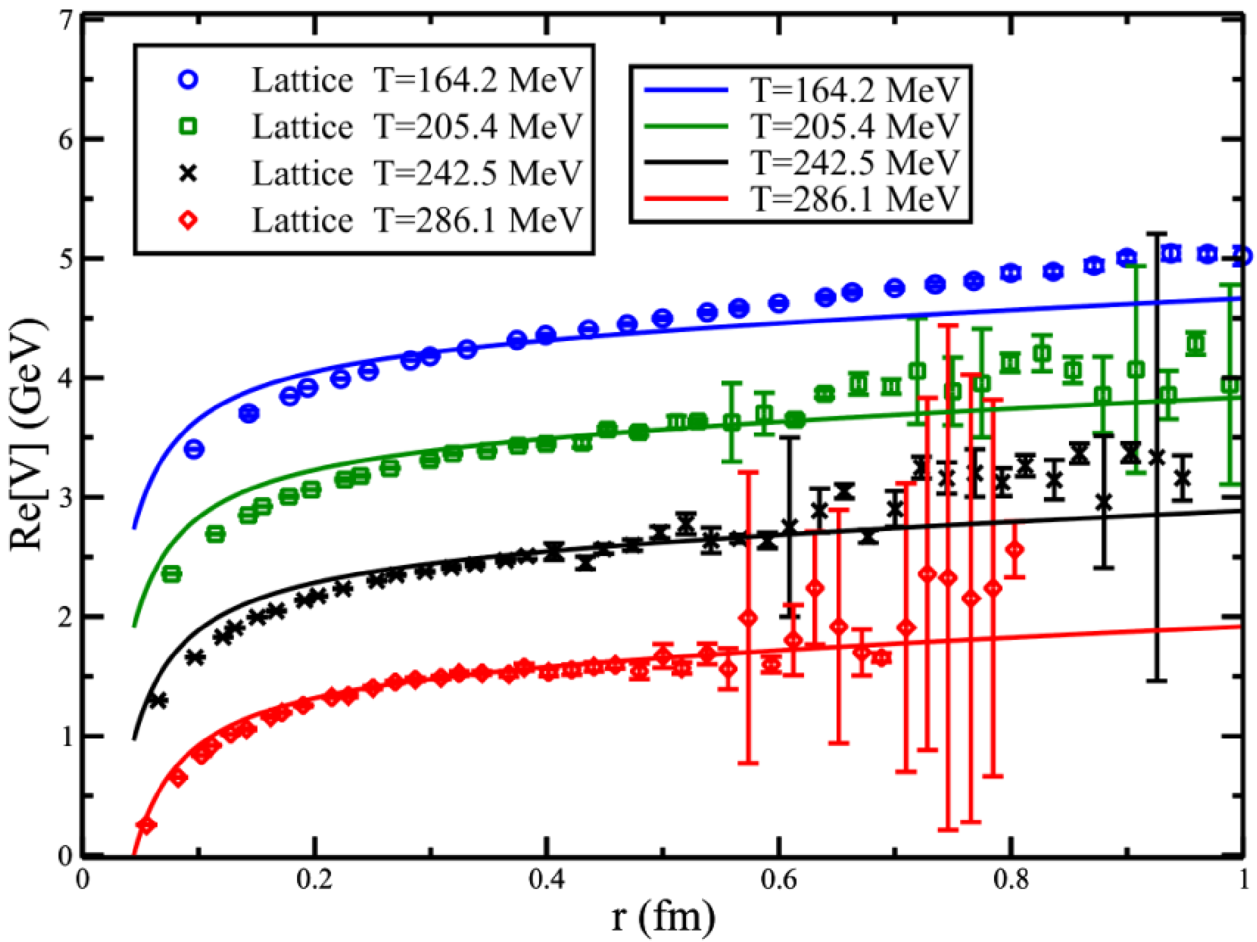
D meson R_{AA} & v_2 from low to high p_T

$$V(r) = V_{\rm Y}(r) + V_{\rm S}(r) = -\frac{4}{3}\alpha_{\rm s}\frac{e^{-m_d r}}{r} - \frac{\sigma e^{-m_s r}}{m_s}$$



Xing, GYQ, Cao, 2112.15062

Heavy quark potential from open HF R_{AA} & v_2



Xing, GYQ, Cao, 2112.15062

Perturbative and non-perturbative interaction between heavy quark and QGP

$$V(r)=V_{\rm Y}(r)+V_{\rm S}(r)=-\frac{4}{3}\alpha_{\rm s}\frac{e^{-m_d r}}{r}-\frac{\sigma e^{-m_s r}}{m_s}$$

$$\alpha_{\rm s}=0.27,\ \sigma=0.45\ {\rm GeV}^2$$
$$m_d=2T+0.2\ {\rm GeV}$$
$$m_s=\sqrt{0.1\ {\rm GeV}\times T}$$

$$V(\vec{q})=-\frac{4\pi\alpha_{\rm s}C_F}{m_d^2+|\vec{q}|^2}-\frac{8\pi\sigma}{(m_s^2+|\vec{q}|^2)^2}$$

$$\begin{aligned}i\mathcal{M}&=\mathcal{M}_{\rm Y}+\mathcal{M}_{\rm S}\\&=\overline{u}(p')\gamma^\mu\overline{u}(p)V_{\rm Y}(\vec{q})\overline{u}(k')\gamma^\nu\overline{u}(k)\\&\quad+\overline{u}(p')\overline{u}(p)V_{\rm S}(\vec{q})\overline{u}(k')\overline{u}(k),\end{aligned}$$

$$|\mathcal{M}_{\rm Qq}|^2=\frac{64\pi^2\alpha_{\rm s}^2}{9}\frac{(s-m_Q^2)^2+(m_Q^2-u)^2+2m_Q^2t}{(t-m_d^2)^2}+\frac{(8\pi\sigma)^2}{N_c^2-1}\frac{t^2-4m_Q^2t}{(t-m_s^2)^4},$$

$$\begin{aligned}|\mathcal{M}_{Qg}|^2=&\\&\frac{64\pi^2\alpha_{\rm s}^2}{9}\frac{(s-m_Q^2)(m_Q^2-u)+2m_Q^2(s+m_Q^2)}{(s-m_Q^2)^2}\\&+\frac{64\pi^2\alpha_{\rm s}^2}{9}\frac{(s-m_Q^2)(m_Q^2-u)+2m_Q^2(u+m_Q^2)}{(u-m_Q^2)^2}\\&+8\pi^2\alpha_{\rm s}^2\frac{5m_Q^4+3m_Q^2t-10m_Q^2u+4t^2+5tu+5u^2}{(t-m_d^2)^2}\\&+8\pi^2\alpha_{\rm s}^2\frac{(m_Q^2-s)(m_Q^2-u)}{(t-m_d^2)^2}\\&+16\pi^2\alpha_{\rm s}^2\frac{3m_Q^4-3m_Q^2s-m_Q^2u+s^2}{(s-m_Q^2)(t-m_d^2)}\\&+\frac{16\pi^2\alpha_{\rm s}^2}{9}\frac{m_Q^2(4m_Q^2-t)}{(s-m_Q^2)(m_Q^2-u)}\\&+16\pi^2\alpha_{\rm s}^2\frac{3m_Q^4-m_Q^2s-3m_Q^2u+u^2}{(t-m_d^2)(u-m_Q^2)}\end{aligned}$$

Xing, GYQ, Cao, 2112.15062

Generalized k_T family of jet reconstruction algorithms

- (1) Consider all particles in the list, and compute all distances d_{iB} and d_{ij}
- (2) For particle i, find $\min(d_{ij}, d_{iB})$
- (3) If $\min(d_{iB}, d_{ij}) = d_{iB}$, declare particle i to be a jet, and remove it from the list of particles. Then return to (1)
- (4) If $\min(d_{iB}, d_{ij})=d_{ij}$, recombine i & j into a single new particle. Then return to (1)
- (5) Stop when no particles are left

$$d_{iB} = p_{T,i}^{2p}$$

$$d_{ij} = \min(p_{T,i}^{2p}, p_{T,j}^{2p}) \frac{\Delta R_{ij}^2}{R^2}$$

$$\Delta R_{ij}^2 = (\phi_i - \phi_j)^2 + (\eta_i - \eta_j)^2$$

p=1: k_T algorithm
p=0: Cambridge/Aachen algorithm
p=-1: anti-k_T algorithm